ABSTRACT

EDMUNDS, BROOKE AURORA. Factors Affecting Susceptibility to - and Management of - Postharvest Soft Rot of Sweetpotatoes Caused by *Rhizopus stolonifer*. (Under the direction of Gerald J. Holmes).

Studies were undertaken to explore the relationship of *R. stolonifer* susceptibility with preharvest growing conditions and postharvest handling of sweetpotatoes. Additional studies were also completed to identify effective decay control products.

A three-year study investigated the effect of preharvest conditions on *R. stolonifer* and *Erwinia chrysanthemi* susceptibility. Roots were harvested from 75 sweetpotato fields and information collected including soil samples, weather during the growing season, weed density, and insect injury (153 predictors). Roots were inoculated after 100 days in storage. Mean *R. stolonifer* incidence was 34.9% (standard deviation=31.7%) and mean *E. chrysanthemi* incidence was 51.0% (standard deviation=30.5%). Predictive models were developed using forward stepwise regression to identify predictors of interest, followed by mixed model analysis (p-value<0.05) to produce a final model. *R. stolonifer* susceptibility is best predicted by soil calcium (% CEC), plant-available soil phosphorus, soil humic matter (%), mean air temperature, mean volumetric soil moisture at 40 cm, and mean soil temperature at 2 cm (all over the growing season). *E. chrysanthemi* susceptibility is best predicted by soil pH and days that soil temperature exceeds 32 ºC (14 days pre- harvest).

Studies were also conducted to define the relationship between postharvest handling and susceptibility to *R. stolonifer*. Experiments designed to simulate packingline handling found root ends are more susceptible that mid-sections and that increasing the number of

time a root is dropped as well as increasing the impact force resulted in increased decay susceptibility. ‘Hernandez’ roots were significantly more susceptible than ‘Beauregard’ in all experiments. To confirm the relationship of impacts and disease development, Beauregard roots were sampled from locations along commercial packinglines. High decay in inoculated as compared to non-inoculated roots indicates that wounding is occurring that could result in disease if the pathogen was present at higher levels.

Evaluations of reduced-risk fungicides, bio-fungicides and generally recognized as safe products for efficacy against *R. stolonifer* found that reduced-risk chemistries boscalid+pyraclostrobin and fludioxonil significantly reduced *R. stolonifer* development and performed similarly to dicloran. *Pseudomonas syringae* based products were moderately effective although results were extremely variable among tests. Generally recognized as safe treatments were ineffective by testing methods used.

Factors Affecting Susceptibility to - and Management of - Postharvest Soft Rot of Sweetpotatoes Caused by *Rhizopus stolonifer*

by
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BIOGRAPHY

Brooke Aurora Edmunds was born on September 22, 1977 in Roseburg, Oregon to Doug and Jean Edmunds. While attending Sauk Valley Community College in Dixon, IL she because interested in biology and botany. Brooke pursued her interests at Iowa State University in Ames, IA and earned a bachelor's degree with honors in Plant Health and Protection. While pursuing her undergraduate degree, Brooke worked in the Plant Disease Clinic and in the research lab of Dr. Mark Gleason. Her undergraduate research project was expanded in a master's degree which she obtained in 2003. Her MS project focused on crown rot of hosta caused by *Sclerotium rolfsii* var. *delphinii*. In 2004, Brooke decided to pursue a PhD in Plant Pathology with Dr. Gerald Holmes. She chose this particular project because of her interest in pursuing a career in Extension education and knew that it would prepare her well. Her degree requirements were completed in Fall 2008 and she has accepted a Regional Extension Specialist position with Colorado State University Extension.

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CHAPTER 1 REVIEW OF RELEVANT LITERATURE

INTRODUCTION

The sweetpotato (*Ipomoea batatas* Lam.) is a member of the morning glory family (*Convolvulaceae*). Alternate common names depend on geographic location and include sweet potato (two words), yam, batata, boniato, camote and kumara. Worldwide, sweetpotatoes are the seventh most important food crop, with most production centered in China (FAO, 2006). In the United States (U.S.), sweetpotatoes are a significant crop, with North Carolina producing approximately 37% of the U.S. crop in 2002 (USDA, 2004). Other states with large sweetpotato acreages include California, Louisiana, Mississippi, and Alabama.

Sweetpotatoes are vegetatively propagated and transplanted as slips (vine cuttings) in the spring (May-June). The slips are produced in plant beds in early spring (March-April) where small roots are 'bedded' under a thin layer of soil and allowed to sprout. The sprouts grow to a length of 21-26 cm before being cut by hand above the soil line and directly planted 4-5 m deep in the production fields. A mature sweetpotato plant consists of above ground vines and three types of roots; fibrous roots, pencil roots (thickened, lignified roots) and storage roots. Storage roots are the economically important portion of the crop in the U.S. Storage roots are not heaviliy lignified and consist of periderm, cortex, and pith tissue containing vascular bundles (also called root fibers) (Artschwager, 1924). The periderm and vascular bundles become slightly lignified as the root develops.

Sweetpotatoes have an indeterminate growth habit with storage root length and diameter determined by the length of time in the field, environmental conditions, and competition from neighboring plants. Consequently, harvest occurs within a relatively wide window of time (90 and 120 days after planting). Harvest is accomplished using a combination of mechanization and hand labor. Roots are dug and brought to the soil surface using specialized plows or chain diggers. Then, hand labor is used to transfer the roots to 20-bushel or 40-bushel capacity palletized bins. The roots remain in these bins through the curing and storage period.

Immediately following harvest, the bins are transported to specialized storage rooms and the roots are cured by exposure to 29°C and 85-90 % relative humidity with ventilation. After five to seven days, the room temperature is dropped to long-term storage temperature of 13°C. The curing process results in better long-term storage because the high heat and humidity aids in healing wounds that occur during harvest (resulting in reduced weight loss and disease) and increases periderm adherence during the packing process. In the U.S., sweetpotato roots are commonly stored for up to twelve months after harvest, enabling producers to provide a year round supply.

Sweetpotatoes are classified into five grades by the United States Department of Agriculture, with the U.S. #1 grade receiving the highest premium. The grades are defined by root length, diameter, and damage by insects, handling or disease. The layout of individual sweetpotato packinglines varies, but all function to remove clinging field soil and sort the roots by grade. The packing process begins when the pallet bins are brought out of storage and the roots are poured into a large tank of water using either a forklift or mechanized system. A conveyor belt brings the roots out of the water and onto a series of overlapping components that further remove soil by brushes and water sprays, apply fungicides, sort by grade and defects, and load the roots into fiberboard cartons. The cartons are stacked by hand onto pallets. The pallets are usually loaded the same day onto semi-truck trailers and transported to market. Markets for U.S. sweetpotatoes may be local, regional, or national. The export market, primarily to the European Union, tripled in size between 1997 and 2002 (Picha, 2005). The extended transport time for export shipments increases the likelihood of excessive weight loss or decay developing.

BIOLOGY OF RHIZOPUS STOLONIFER AND DISEASE CYCLE ON SWEETPOTATO

Sweetpotatoes are susceptible to a number of diseases during the postharvest storage period and during shipping (Harter et al, 1918; Clark and Moyer, 1988). The most common are Rhizopus soft rot (*Rhizopus stolonifer*), bacterial soft rot (*Erwinia chrysanthemii*), Fusarium root rot (*Fusarium solani*), Fusarium surface rot (*Fusarium oxysporum*), and black rot (*Ceratocystis fimbriata*). Both *Ceratocystis* and *Fusarium* decays can be controlled by proper curing and storage conditions. Bacterial soft rot is not a major postharvest disease in North Carolina. *R. stolonifer*, however, is a problematic pathogen as it infects fresh wounds occurring during packing and shipping. There is limited data on the exact losses attributed to Rhizopus soft rot. A study conducted in the New York City retail market found that the majority of culls due to disease were caused by Rhizopus soft rot (~2% decay in survey) (Ceponis and Butterfield, 1974). This figure does not include any losses prior to reaching the retail market. Anecdotal reports suggest that Rhizopus soft rot is unpredictably sporadic and generally results in heavy losses to entire shipments when it does occur.

R. stolonifer has a wide host range and can affect over 300 plant species including fruits, vegetables, and ornamentals (Farr *et al*, 2007). *R. stolonifer* (Ehrenb. ex Fr.) (syn *R. nigricans*) was first described in 1818 (Lunn, 1977) and first recognized as a pathogen on sweetpotato in 1890 (Halstead). Lauritzen and Harter (1923) determined that *R. tritici* (syn. *R. arrhizus*) is also capable of causing soft rot on sweetpotatoes, however, *R. stolonifer* is more commonly associated with postharvest infections as it out-competes *R. arrhizus* and other *Rhizopus* spp. at lower temperatures (14-18°C) (Harter and Weimer, 1921; Lauritzen and Harter, 1923).

Symptoms of *R. stolonifer* infection include rapid development of a watery soft rot of the internal portion of the storage root with the periderm generally remaining intact. Infection can occur anywhere on the root but usually initiates at the ends due to the inevitable wounding resulting from harvest, or because a root's tapered ends are more likely to be injured. Rhizopus soft rot produces a characteristic fermentation odor (Clark and Moyer, 1988). Roots may dry and mummify with only the periderm and root fibers remaining intact because of the inability of the fungus to breakdown the lignin in these components. Characteristic signs of Rhizopus soft rot include the production of tufts of white hyphae which break through the surface of the root and produce large numbers of brown-black sporangiophores (34 µm diam. by 1000-3500 µm length) which support a sporangium (100-350 µm diam.). Sporangiospores (4-11 µm diam) are produced in the sporangium and are unicellular, ovoid and brown. Sporangiospores serve as the primary inoculum and are passively released when the outer layer of the sporangium breaks down. Other *R. stolonifer* structures include stolons and rhizoids. Stolons arch over the surface and rhizoids grow into the substrate at each point of contact between stolon and substrate.

Sexual recombination is rare and occurs when mycelium of two compatible strains come in contact. Progametangia from each strain grow towards each other and fuse into gametangia, forming a thick-walled zygospore. Zygospores germinate to form sporangiophores bearing a single sporangium.

R. stolonifer is incapable of breaching the intact root periderm and requires a wound to initiate infection. The type of wound influences infectivity, with smooth wounds less likely to be infected than impact bruise/crushed tissue wounds (Lauritzen, 1935; Srivastava and Walker, 1959; Clark and Hoy, 1994; Holmes and Stange, 2002). It has been suggested that smooth wounds (slices or scrapes) lack the quantity of nutrients required for spore germ tube formation (Srivastava and Walker, 1959). No research has been completed to identify the degree of impact bruising required for infection to be initiated.

R. stolonifer relies on cell wall degrading enzymes to infect (Harter and Weimer, 1923). Even though a germ tube is not visible, germinating spores produce pectinolytic enzymes (pectin methyl esterase, polygalacturonase, and pectin depolymerase) (Weimer and Harter, 1923; Srivastava et al, 1959) and hyphae generate pectinolytic enzymes followed by cellulolytic enzymes after 3 days (Spalding, 1963). These enzymes break down the middle lamella causing cells to separate and the tissue to die, allowing invasion by the hyphae.

Optimum conditions for infection are 20-23°C and 75-84% relative humidity (Lauritzen and Harter, 1925; Srivastava and Walker, 1959). At 18.5-23°C infection can occur in 43 hours or less, with more time required at lower temperatures (Lauritzen and Harter, 1925). *R. stolonifer* is easily grown on common media such as potato dextrose agar. Optimal conditions for growth on media are 25-28°C (Weimer and Harter, 1923; Srivastava and Walker, 1959) and a pH of 4.5 (Srivastava et al, 1959).

MANAGEMENT OF RHIZOPUS SOFT ROT

Effective management strategies for Rhizopus soft rot on sweetpotato include resistant varieties, proper curing after harvest, and decay control product applications on packinglines.

Resistant varieties. The sweetpotato industry readily accepts new cultivars, which leads to a quick shift in the most widely grown cultivar. Beauregard, released in 1987, is currently the dominant cultivar grown in the U.S. (Rolston et al., 1987). In the last ten years, seven new cultivars have been released in the U.S.: Bienville (La Bonte et al., 2003), Carolina, Covington (Yencho, personal communication), Ruby (Collins et al., 1999), Evangeline (La Bonte et al., 2008), Ruddy (Bohac et al., 2002), and White Regal (Bohac et al., 2001). Yield and quality characteristics, rather than disease resistance, are the primary focus of modern breeding efforts. Rhizopus soft rot resistance screening is used to describe most newly released cultivars, but is not a primary selection factor used by breeders. The method of testing Rhizopus resistance is usually not specified and/or may vary between research groups, making direct comparisons difficult using only the information from the cultivar release publication.

Replicated resistance screening of modern cultivars and breeding lines showed that white-fleshed cultivars tend to be more susceptible than orange-fleshed cultivars (Clark and Hoy, 1994). Notable exceptions included cv. Hernandez and Jewel, which are both orange fleshed and moderately susceptible to *R. stolonifer*. Holmes and Stange (2002) confirmed that cv. Hernandez is more susceptible than cv. Beauregard when injured. Beauregard is considered to be moderately resistant to *R. stolonifer* although sporadic, heavy losses during shipping are known to occur. No cultivar has been found that is completely resistant to Rhizopus soft rot.

Curing. Curing immediately after harvest generally eliminates losses to *R. stolonifer* by healing wounds occurring during harvest. The current recommended curing process is to expose the roots to high temperature (29°C) and high relative humidity (90%) for five to seven days (Kushman, 1975). The time length is important because increased sprouting (a negative quality in stored roots) can result if roots are held at high temperatures for extended periods (Hall, 1992). Curing induces suberization of wounds followed by new periderm formation (this process was called wound 'cork' or 'phellum' in early research), effectively healing the wounds (Weimer and Harter, 1921). The new periderm consists of three to seven layers of flattened cells, with the first layer formed after four days in the curing environment (Walter and Schadel, 1982; Walter and Schadel, 1983; Strider and McCombs, 1958).

McClure (1959) and Tereshkovich and Newsom (1964a) suggested that re-curing prior to shipping would adequately heal wounds occurring during the packing process, resulting in reduced loss to decay. This may be sufficient for healing skinning injuries, but wound periderm formation has been found to be irregular in bruise type wounds (Daines, 1943; Strider and McCombs, 1958). Commercial packinghouses have not embraced re-curing as a management strategy due to the time and resources required to raise the root temperature to 29 C, which is required for re-curing to be effective (McClure, 1959; Tereshkovich and Newsom, 1964a). McClure (1959) suggested a hot water dip to quickly boost root temperature but this may result in additional problems such as infection by other pathogens or increased sprouting during transport.

Decay control products. *R. stolonifer* is most commonly managed by packingline applications of dicloran (also known as DCNA or Botran®). Dicloran, a chlorinated nitro-aniline, is a broad spectrum fungicide registered for postharvest use on sweetpotatoes and in-field use for several fruits, vegetables, and ornamentals. Use of dicloran on sweetpotatoes to control Rhizopus soft rot was first reported in 1964 (Martin). Dicloran is considered by the Fungicide Resistance Action Committee (FRAC) to be at low to medium risk for resistance development. Forced resistance has occurred in culture when *R. stolonifer* was grown on dicloran-amended media (Webster et al, 1968); however, no additional reports have been published on this phenomenon. Another fungicide, SOPP (sodium o-phenylphenol), was developed in the mid-1950's and used for Rhizopus soft rot control of sweetpotatoes for many years. SOPP is considered more difficult to work with than dicloran, as SOPP is corrosive to the skin and mucous membranes (i.e., eyes and throat). There also have been anecdotal reports of negative effects on root quality including root skin color changes. SOPP registrations were dropped in 2005. As of 2005, no commercial fungicides or decay control products, other than dicloran, were labeled for control of Rhizopus soft rot on sweetpotatoes.

New chemistries have been tested for postharvest use on fruits to control Rhizopus soft rot. Commercial formulations of boscalid alone and boscalid + pyraclostrobin were effective in the control of Rhizopus on strawberry (Sallato et al., 2007). A boscalid+pyraclostrobin treatment also significantly reduced postharvest decay of Rhizopus fruit rot of nectarine with two preharvest applications within eight days of harvest (Holb et al., 2005). Boscalid+pyraclostrobin is the active ingredient in Pristine® which is registered for preharvest treatements to control Rhizopus soft rot on stone fruits.

Fludioxonil is another new chemistry which shows promise for controlling Rhizopus soft rot of sweetpotato. *R. stolonifer* is considered sensitive to fludioxonil in vitro with an ED_{50} ranging from 0.01 to 0.09 mg/L (Olaya et al., 2007). Postharvest applications of fludioxonil effectively controlled Rhizopus soft rot of peaches, plums, and nectarines (Förster et al., 2007; Northover and Zhou, 2002; Yoder et al., 2001). Prior to 2002, there were no published studies on the use of fludioxonil on sweetpotatoes. Fludioxonil is the active ingredient in Scholar® which is labeled for postharvest applications to control Rhizopus soft rot of stone fruits.

There has been a growing interest in the use of biological control organisms for control of postharvest diseases of fruits and vegetables. As of 2002, no commercial formulations were registered for use against *R. stolonifer* (McSpadden Gardener and Fravel, 2002).

In recent years, studies have identified biological control organisms effective against Rhizopus soft rot on fruit. Application of a *Trichoderma harzianum* Rifai emulsion reduced the *Rhizopus* lesion size in apple, pear, peach, and strawberry (Batta, 2007). A yeast antagonist, *Cryptococcus laurentii*, effectively controlled postharvest decay of strawberry by *Rhizopus stolonifer* when applied alone or following a hot water dip (Zhang et al., 2007). Preharvest applications of the yeast *Metschnikowia fructicola* reduced postharvest decay on strawberries caused by a mixed infection of *R. stolonifer* and *Botrytis cinerea* (Karabulut et al., 2004). *Pichia membranefaciens*, another yeast antagonist, completely inhibited Rhizopus soft rot of peach when applied at a high concentration (Qing and Shiping, 2000). Several bacterial antagonists have been identified as effective against *R. stolonifer*. Strains of *Pantoea agglomerans* reduced Rhizopus soft rot on plum (Frances et al. 2006), apple, pear (Nunes et al., 2001), peach, apricot and nectarine (Bonaterra et al., 2003). Another bacterium, *Enterobacter cloacae*, reduced Rhizopus decay on peach (Wilson et al., 1987). *Pseudomonas syringae* strain ESC-10 (available commercially as Bio-Save 10LP) significantly reduced Rhizopus decay in peaches (Northover and Zhou, 2002). No organism has been identified with effectiveness in controlling *R. stolonifer* infection of sweetpotato.

Surface and water disinfectants/sanitizers have also been considered for use in controlling postharvest *R. stolonifer* infections by reducing the spore load in packingline wash water. Chlorine is the most commonly used water sanitizer in the produce industry. Chlorine added to hydrocooling and dump tank water was ineffective in controlling the development of Rhizopus soft rot on strawberries and tomatoes (Ferriera et al., 1996; Vigneault et al., 2000; Bartz et al., 2001). An in vitro study showed that volatile chlorine was able to reduce Rhizopus spore germination and mycelium growth (Avis et al., 2006). Applications of volatile chlorine also significantly reduced postharvest Rhizopus development on table grapes and strawberries (Lisker et al., 1996; Avis et al., 2006). These studies are in the preliminary stages and issues addressing human health and metal oxidation of equipment (common concerns with chlorine use) have not been investigated.

A more recently developed sanitizer is peroxyacetic acid (PAA), a strong oxidizer, available in commercial formulations such as Oxidate®, Tsunami 100®, and StorOx®. Narciso et al. (2007) found what they thought was a residual effect of preharvest PAA sprays on strawberries, which significantly reduced postharvest decay attributed to combined *Botrytis* and *Rhizopus* infection. In reality, the preharvest applications functioned to reduce the spore numbers on the fruit rather than having a residual effect.

Copper ionization is a water treatment using charged copper ions to reduce microbial counts of human pathogens in swimming pools and drinking water. There is interest in using ionization in postharvest systems as an alternative to chlorine. There is only anecdotal evidence to suggest that postharvest quality is improved by using copper ionized treated water on sweetpotato packinglines. No systematic studies on the control of plant pathogens have been completed.

Calcium chloride has been used alone or in combination with biological control agents to enhance the effectiveness of disease control. Postharvest dip treatments of calcium chloride significantly reduced the development of brown rot of peach (caused by the fungus *Monilinia laxa*) (Thomidis et al., 2007). Qing and Shiping (2000) found a significant increase in the efficacy of a yeast antagonist against *R. stolonifer* on nectarines when applied in combination with a 2% (wt/v) solution of calcium chloride. The proposed mode of action of the calcium treatment is to reduce the activity of cellulolytic enzymes produced by pathogens (Wisniewski et al., 1995).

Other decay control techniques are in development; plant and fungi-derived volatile compounds and ultraviolet light treatments have shown promise for controlling postharvest diseases of fruits and vegetables caused by *R. stolonifer*. Effectively functioning as fumigants, volatiles have an advantage over liquid decay control products as the commodity remains dry (especially important for moisture-sensitive fruit such as strawberries and cut flowers) and can be used during transit. Limited research has identified plant-derived volatiles which reduce in vitro *Rhizopus* mycelial growth, including acetaldehyde, benzaldehyde, and cinnamaldehdye (Avissar and Pesis, 1991; Utama *et al*, 2002). In 2001, the fungus *Muscador albus* was found to emit powerful volatiles capable of reducing the growth of other fungi (Strobel et al., 2001). Controlled studies found these volatiles were able to reduce *R. stolonifer* growth in vitro (Mercier and Jimenez, 2004). None of these volatile treatments are ready for commercial implementation.

Exposing tomatoes and sweetpotatoes to low dose ultraviolet light (UV-C, 254 nm) for 5-7 minutes resulted in a significant reduction in Rhizopus soft rot development as a result of an induced resistance response in preliminary trials (Stevens et al., 1997; Stevens et al., 2004). The effect of UV-C treatments (also referred to as radiation hormesis) on quality characteristics of sweetpotatoes is unknown, although the no external damage was seen in these trials. This research holds promise as a non-chemical management method which could be incorporated into existing packinglines; however, commercial scale research has not been completed.

In summary, alternative fungicides, biological controls and other treatments are capable of reducing decay caused by *R. stolonifer*. None have been tested on sweetpotatoes.

There is a pressing need to identify and label effective alternative decay products and treatments as dicloran use is prohibited in many markets, including the European export market and buyers for infant food companies.

PREHARVEST FACTORS AFFECTING *RHIZOPUS* SUSCEPTIBILITY

It is known that preharvest factors (irrigation, fertilizer levels, and environmental conditions, etc.) affect the postharvest quality of vegetables. Research on the relationship between preharvest conditions and postharvest sweetpotato quality is limited and is focused on quality factors such as yield, sugar content and baking qualities rather than disease susceptibility. There has been minimal research on the effect of preharvest stress on the keeping quality among different sweetpotato cultivars, but no information on the effect of different growing conditions within a single cultivar. No research has been published on the predisposing factors related to sweetpotato susceptibility to *R. stolonifer*.

Soil nutrition. Research on the interaction between soil nutrient levels and disease susceptibility of sweetpotatoes is focused on the soilborne field diseases soil rot/pox (caused by *Streptomyces ipomoea*) and black rot (caused by *Ceratocystis fimbriata*). There is no research relating preharvest soil factors to disease which initiates postharvest.

Published studies instead focus on the interaction of nitrogen fertilization rates on yield and quality (root size and shape). There is a marked response of increased yield in Beauregard sweetpotatoes to increasing nitrogen fertilization treatments (Phillips et al., 2005; Villagarcia et al., 1998). Phillips et al. (2005) found an interaction between fertilizer rate and application timing (pre-plant or early season) which affected the percent of roots which developed into U.S. #1 grade.

Entomological research has studied the ecology (feeding, larva survival, oviposition habits, etc.) of the sweetpotato weevil (*Cylas formicarius elegantulus*) as related to sweetpotato root surface chemistry. Mao et al. (2001) found that high levels of nitrogen fertilization increased caffeic acid concentration in the root periderm and reduced feeding by the sweetpotato weevil.

No research has been done which correlates postharvest qualities to other soil nutrients such as potassium and phosphorus.

Soil temperature and moisture. Sweetpotatoes are known to be affected by temperature and moisture levels in the soil during the growing season. A study of the effect of temperature and soil moisture near harvest showed that cv. Porto Rico grown in Louisiana was occasionally more susceptible to postharvest decay when harvested from a field that experienced a cold wet period prior to harvest (Kushman et al., 1954). Unfortunately, the pathogen was not specified. As a follow-up study, the researchers continued to examine the effect of environmental conditions and date of harvest on keeping quality of cv. Porto Rico (Kushman and Deonier, 1958). They extended the harvest season into December and confirmed that cold, wet soils decrease sweetpotato quality by increasing internal breakdown.

Ton and Hernandez (1978) found that shrinkage and decay at harvest was significantly higher for roots exposed to very wet soil (field irrigated at 1.72 cm/h for 72 h two days prior to harvest). Ahn et al. (1980) expanded on this work with a growth chamber study comparing the effect of temperature and flooding. They found that roots grown in warm (24-34°C), water-saturated soils for one week prior to harvest had the most root decay and quality reductions. Less decay was reported in roots grown in cold (4°C), water-saturated soils and in the non-saturated soils at either warm or cold temperatures. Unfortunately, this study also did not report the specific organism causing the decay. A field study using 'Jewel' and 'Centennial' was conducted to evaluate the effect of flooding for 1, 2, or 3 days immediately prior to harvest (Corey, et al., 1982). As expected, heavier losses (due to weight loss and unspecified rot) were experienced with a longer flood period. The authors also found an effect of the type of soil with 'Jewel' roots; saturated silt loam soils resulted in significantly higher postharvest losses compared to roots from saturated sandy loam soils. The authors suggested that the silt loam did not drain as fast as the sandy loam soil, thus exposing the roots to the flood stress for a longer period of time.

Soil moisture and temperature affect periderm composition which in turn can affect disease susceptibility. A greenhouse study showed that sweetpotatoes grown under drought stress conditions may produce significantly thicker periderm tissue than those grown in a non-stressed environment (Harrison, et al., 2006). This same study also showed that roots grown under drought conditions had a higher level of caffeic acid, a phenolic compound, in the periderm tissue. Villavicencio et al. (2007) studied the effect of three growing temperature regimes on root characteristics such as lignification, periderm adhesion, and pectinase activity. They found a positive correlation between pectinase activity and growth temperature, indicating that temperature has an effect on strength of cell wall bonds. The authors also found a positive correlation between periderm lignification and growth temperature, indicating that roots grown at higher temperatures are likely to be more resistant to compression type injuries.

Phenolic compounds. Phenolic compounds are a large class of plant secondary metabolites implicated in constitutive and induced defense responses to pathogen infection in many plants. Sweetpotato storage roots are known to produce the phenolic compounds chlorogenic acid, dicaffeoylquinic acid, and caffeic acid (Rudkin and Nelson, 1947; Son et al., 1991). The periderm of storage roots accumulates the highest levels of phenolic compounds as compared to the cortex and pith (Son et al., 1991).

Levels of phenolics in storage roots are likely affected by environmental conditions. Harrison et al. (2003) found that caffeic acid levels in sweetpotato periderm varied among cultivars and breeding clones and also demonstrated an interaction between phenolic levels and environmental conditions for two growing locations. Fertilization levels may also affect subsequent root phenolics levels; nitrogen applications (135 kg/ha) significantly increased caffeic acid levels in one year but were insignificant when the study was repeated (Mao et al., 2001). A controlled greenhouse study found that sweetpotatoes grown under drought conditions had a higher level of caffeic acid in the periderm tissue (Harrison, et al., 2006).

Phenolic compounds have recently been implicated in the inhibition of *R. stolonifer*. Stange et al. (2001) found that acetone extracts of the peel (periderm and outer cortex tissue) of cv. Beauregard and Hernandez inhibited *R. stolonifer* mycelial growth. The peel extracts were found to contain caffeic acid and chlorogenic acid. However, the extracts inhibited *R. stolonifer* growth equally between the two cultivars although Hernandez is known be more susceptible to *R. stolonifer* than Beauregard (Clark and Hoy, 1994). Laboratory grade chlorogenic acid has been shown to inhibit hyphal growth of *R. stolonifer* in vitro (Peterson et al., 2005).

POSTHARVEST FACTORS AFFECTING *RHIZOPUS* SUSCEPTIBILITY

Changes in root composition during storage. Sweetpotato root composition changes during extended storage periods. Hasselbring and Hawkins (1915) found that root composition consisted primarily of starch at harvest (exact harvest date was not specified) followed by a slow increase in sugar content peaking from October to March, then decreasing back to primarily starch. More recent studies have shown that starch hydrolyzing enzymes (enzymes that convert starch to sugars) and total sugar content (combined glucose and fructose) increased over time in storage for some cultivars and were variable for others (Morrison et al., 1993; Picha, 1987). The cultivar Beauregard was not included in these experiments.

It is not known how these changes in root composition may relate to disease susceptibility. Holmes and Stange (2002) found Rhizopus soft rot susceptibility in both cv. Beauregard and Hernandez peaks after 100-150 days in storage, before and after which the roots are much more resistant. This peak may be due to physiological changes occurring during the storage period, but these were not measured.

Postharvest handling and decay development. Losses due to injuries sustained during packing and transport is of concern in fruit and vegetable commodities. Early researchers in agricultural engineering recognized the need to quantify and identify the source of impacts occurring during transport and packing. Impact recording devices (IRD's), also called instrumented spheres in early research, were developed for use on packinglines in the late 1970's. These devices contain a triaxial accelerometer to measure peak impact force. The early versions of these devices were spherical and coated in beeswax and/or plastic (O'Brien et al., 1973; Tennes et al., 1986; Klug et al., 1989).

A commercial IRD is available with urethane casings that replicate the shape of popular commodities such as pineapples, apples, Irish potatoes, mangoes and peaches (Sensor Wireless, Charlotte, Canada). The casing fits tightly over the accelerometer core. This allows the IRD to travel on the packingline and measure impacts experienced by the commodity of interest. (At this time, a sweetpotato-shaped casing is not commercially available.) Another technical improvement is the ability to remotely detect impacts through the use of radiosignal technology. This allows the operator to transfer data in real-time to a hand-held device without having to disassemble the IRD to download the data. This greatly improves on-site educational opportunities for packingline managers and workers. Increased data storage capacities have also greatly improved the ease of use of these devices.

Several attempts have been made to create statistical models relating postharvest impacts and subsequent bruising for fruits and vegetables. IRD's and pendulums equipped with accelerometers have been used to develop bruise thresholds for onion, apple, potato, and tomato (Pang et al., 1994; Bajema and Hyde, 1995; Mathew and Hyde, 1997; Van linden et al., 2006). The standard method for developing a bruise threshold is to measure impacts and associated bruising resulting from controlled drops from known heights onto different impact surfaces which mimic the level of impacts occurring on a packingline (Pang et al., 1994; Bajema and Hyde, 1995). The datasets are statistically analyzed to create bruise probability or ‘potential bruise boundary’ models. The most common values incorporated into these models are fruit characteristics (variety, mass, degree of ripeness), location of the impact on the fruit, drop height, impact surface, and peak impact. As expected, fruit mass and degree of ripeness (which is directly related to flesh firmness) are important factors in the development of bruises. Researchers have used different IRD’s, which makes direct comparisons of the impact/bruise data difficult among publications. Bruise probabilities are also highly specific and results can not be extrapolated to other commodities.

There is minimal research relating packingline damage to decay development in fruit and vegetable commodities, including sweetpotatoes. An anecdotal report out of California showed that drops over 1cm onto a steel surface significantly increased *Monilinia fruticola* development in inoculated peaches and nectarines (Crisosto, 1999). These impacts also increased water loss (measured by weight loss) and resulted in reduced physical appearance. Shellie (1997) reported on a survey of grapefruit packinglines in which four impact rating categories (ranging from ‘most likely not damaging’ to ‘very likely damaging’) were assigned to packinglines based on previous controlled drop studies. Surface scuffing and surface mold were measured and compared between impact categories (the surface mold organism was unspecified). Scuffing was measured using a triphenyl-tetrazolium chloride dye test which stains the white pith of grapefruits a bright red allowing easy visual estimation of damaged areas. The dye test was found to correlate well to abrasion injury but not to injury from drops. The authors did not find a relationship between scuffing on packinglines and surface decay development, which is likely due to fungicides and waxes used on the packinglines.

Sweetpotatoes suffer three types of injuries during the packing process: skinning, when the periderm is sloughed off; broken ends, when the long, thin root tips are broken off; and bruising, when the root tissue is crushed from bounces and drops on packingline surfaces. A bruise injury on a sweetpotato is different from those on other commodities. The bruised cells are crushed although the tissue does not soften significantly or oxidize to a brown color as do apples or potatoes. This is due to minimal air space between cells and a lack of enzymes involved in oxidation. These injuries, however, do result in increased weight loss and increased potential for decay development.

Skinning is known to result in increased weight loss and is a common site for *Penicillium* mold growth. Skinning occurs on most roots during harvest and packing, however different degrees of sensitivity to skinning exist between cultivars and even within a cultivar, depending on environmental conditions. Blankenship and Boyette (2002) studied the effect of different temperatures and humidity regimes during curing and found variable results in degree of skinning among the five cultivars studied. The authors speculated that environmental conditions and root maturity were related to the degree of skinning and they used this to explain the variability they observed. Villavicencio et al. (2007) studied the effect of three growing temperature regimes on root periderm adhesion and found a negative correlation between skinning and preharvest growth temperature. This may be related to changes in periderm composition as previously described.

Broken end damage to sweetpotatoes results when the long thin root ends are snapped off, either deliberately by packingline workers or as a result of the packing process. No studies have been completed correlating weight loss to broken ends, although shriveled ends are a recognized quality issue during shipping.

There is limited information on the effect of bruise injuries on sweetpotato quality. It is known that *R. stolonifer* infections are more likely to occur with bruise injuries than with smooth wounds (like those caused by skinning and broken ends) (Lauritzen, 1935; Srivastava and Walker, 1959; Clark and Hoy, 1994; Holmes and Stange, 2002). In these previous studies only a single impact force was tested; the effect of impact bruise severity on susceptibility of sweetpotatoes to *R. stolonifer* is unknown.

RESEARCH OBJECTIVES

R. stolonifer is an important wound-dependent postharvest pathogen of sweetpotato storage roots. The most common management options (resistant varieties and fungicide application) can unpredictably fail and result in heavy losses. It is known that the sensory qualities of sweetpotatoes are affected by environmental stress during the growing season; *R. stolonifer* susceptibility is also likely dependent on growing conditions which affect root physiology. Field observations suggest that there are pre-harvest factors affecting postharvest *R. stolonifer* susceptibility. The first objective of this project was to determine if field-to-field variability in susceptibility to *R. stolonifer* exists and to identify which preharvest environmental and cultural factors result in increased susceptibility.

Postharvest factors are also important to the development of Rhizopus soft rot infection. *R. stolonifer* is much more likely to infect if the wound is a bruise, but little is known about the effect of wound severity on disease development. The second objective was to quantify the impacts occurring on sweetpotato packinglines and determine the effect of the wounds caused by these impacts as they relate to susceptibility to *R. stolonifer*.

Fungicide application is the most common method of *R. stolonifer* management. A single fungicide is currently relied on by the majority of the industry, therefore, the third objective of this project was to evaluate alternative decay control products (including reduced-risk chemistries, biological control products, and generally regarded as safe products/sanitizers) for control of Rhizopus soft rot in sweetpotatoes.

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CHAPTER 2. RELATIONSHIPS OF WEATHER CONDITIONS AND SOIL FACTORS TO SUSCEPTIBILITY OF SWEETPOTATOES TO POSTHARVEST DECAY CAUSED BY *RHIZOPUS STOLONIFER* AND *ERWINIA CHRYSANTHEMI*.

The following chapter is in preparation to be submitted to the journal Crop Science.

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ABSTRACT

Postharvest soft rot diseases of sweetpotatoes caused by *Rhizopus stolonifer* (Rhizopus soft rot) and *Erwinia chrysanthemi* (bacterial root rot) occur sporadically and can result in high losses. A three-year field study investigated the relationship of preharvest conditions to postharvest susceptibility to both diseases. Preharvest information was recorded in 75 North Carolina sweetpotato fields including soil texture, chemistry and fertility; air temperature, soil temperature and soil moisture during the growing season and in the 28 days prior to harvest; thresholds for low air temperature and high/low soil temperature and soil moisture; weed density; insect injury; and rotation crop (153 total predictors). Roots were sampled from each field and inoculated with each pathogen after 100 days in storage. Disease susceptibility was measured as incidence of symptomatic roots 10 days following inoculation. Mean Rhizopus soft rot incidence was 34.9% (standard deviation=31.7%) and mean bacterial root rot was 51.0% (standard deviation=30.5%). Disease incidence was correlated to each of the preharvest predictors. Predictive models for both diseases were

built by first using forward stepwise regression to identify predictors of interest, followed by a mixed model analysis (p-value<0.05) to produce a final reduced model. There was a significant effect of year in both models. Postharvest Rhizopus soft rot susceptibility can be predicted by the percent of the soil cation exchange capacity occupied by calcium, the amount of plant-available soil phosphorus, percent soil humic matter (%), the mean air temperature over the growing season, mean volumetric soil moisture at 40 cm over the growing season, and the mean soil temperature at 2 cm over the growing season. Postharvest bacterial soft rot susceptibility can be predicted by soil pH measured at harvest and the number of days in which soil temperature exceeds 32 ºC in the 14 days prior to harvest.

INTRODUCTION

Sweetpotato (*Ipomoea batatas* Lam.) is the seventh most important food crop, with most production centered in China (FAO, 2006). In the United States (U.S.), sweetpotatoes are a significant crop, with North Carolina producing approximately 37% of the U.S. crop in 2002 (USDA, 2004). Postharvest diseases are a constant threat and are especially costly as all expenditures of growing, harvesting and storage have already been incurred by the producer. Some diseases, like those caused by *Fusarium oxysporum*, *F. solani* and *Ceratocystis fimbriata* develop slowly during long-term storage. Other diseases, such as Rhizopus soft rot and bacterial root rot, develop very rapidly during transit to market and are of great concern due to the amount and timing of losses.

Rhizopus soft rot, caused by the fungus *Rhizopus stolonifer* (syn. *R. nigricans*), is the most common postharvest disease of sweetpotatoes (Clark and Moyer, 1988). It causes a watery, soft rot that can result in high, yet sporadic, losses. *R. stolonifer* requires a wound for infection to occur (Lauritzen, 1935; Srivastava and Walker, 1959) and the injuries that occur during the packing process provide an infection court for Rhizopus soft rot development. For this reason, the majority of sweetpotato packers use prophylactic fungicide applications as "insurance" against Rhizopus soft rot. Anecdotal evidence suggests that prophylactic fungicide applications may not be necessary as there is variation in Rhizopus soft rot susceptibility among fields and among and between growing seasons. However, the source of this variability has not been confirmed with systematic studies.

Bacterial root rot, caused by *Erwinia chrysanthemi* (syns. *Pectobacterium chrysanthemi* and *Dickeya chrysanthemi*), is a less common disease of sweetpotato and occurs sporadically (Clark and Moyer, 1988; Schaad and Brenner, 1977). The symptoms of postharvest bacterial soft rot include a brown watery soft rot with or without a dark brown margin surrounding the decayed area. Oxygen deprivation and exposure to high heat (>30 ºC) are contributing factors to postharvest disease development. Thus, one control method available is to avoid these conditions during storage and transit to market.

The sporadic incidence of both diseases under nearly identical postharvest conditions (e.g., curing, storage, and packing) leads one to question if there are events or conditions occurring preharvest that affect postharvest susceptibility to disease. A comprehensive strategy for management of these diseases requires identification of the factors which are related to increased disease susceptibility. The objectives of this study were to 1) determine if field-to-field variability in disease susceptibility within and among growing seasons exists; 2) determine if susceptibility to *R. stolonifer* and *E. chrysanthemi* is related; and 3) identify the predisposing environmental conditions and agronomic practices that correlate to postharvest susceptibility of sweetpotatoes to *R. stolonifer* and *E. chrysanthemi*.

MATERIALS AND METHODS

Sweetpotato roots (cv. Beauregard) were collected from 75 fields under commercial production in North Carolina (32 fields in 2004, 27 in 2005 and 16 in 2006) (Figure 2.1). New field locations were selected each year of the study (i.e., field locations were not repeated). This study was part of a larger multidisciplinary integrated pest management investigation; therefore, field selection was made to meet experimental goals for integrated pest management in collaboration with weed science and entomology. Within each commercial field, 16-32 rows were designated as the experimental area. The length of the rows varied with individual fields but was at least 30 m long. Within this area, the experimental design was a split plot with two replications that compared insecticide treated beds (8-16 rows) to non-insecticide treated beds (8-16 rows). The specific insecticides and number of applications were selected at the discretion of the individual growers. Other than the insecticide treatment, the experimental area was cultivated using practices at preference of the individual grower.

Harvest dates, based on root size and weather conditions, were determined by the grower. At harvest, a single row plow was used to bring roots to the soil surface. One row in the middle of each split plot treatment was sampled. Within this row, two 9.2 m plots were marked out for each replication and 50 U.S. No. 1 grade roots (length between 7.6 to 22.9 cm, diameter between 4.5 to 8.9 cm, maximum weight <567 g) were collected from within the plot. Roots were placed into ventilated plastic crates and transported to a storage facility. All roots were cured at 29.4 C for 5 days and then stored at 15.6-18.3 C until inoculation (at 100 days of storage).

Environmental factors. Hourly weather data for the growing season was modeled for each field site using the SkyBit service (ZedX, Inc; Bellefonte, PA). The set of weather parameters estimated by SkyBit included air temperature, soil temperature (at depths of 2 and 4 cm), and soil moisture (at depths of 10, 40, and 100 cm) (Table 2.1). The hourly data was averaged into daily means and used to calculate growing season averages and averages for the four weeks prior to harvest (7 d, 14 d, 21 d, and 28 d pre-harvest) for each field. Threshold variables were calculated from the estimated weather data and included low air temperature, high/low soil temperature (at depths of 2 and 4 cm), and high/low soil moisture (at depths of 10, 40, and 100 cm) (Table 2.1). A threshold was considered to have occurred if the variable's defined limits were exceeded for at least one hour in a 24 hour period. For example, if soil temperature dropped below 13ºC for any single hour in a day (1:00-24:00) that day was considered to be a "low soil temperature" day. The threshold definitions are based on preliminary research underway to define environmental stress as related to sweetpotato growth and yield (A. Villordan, personal communication).

Agronomic factors. Composite soil samples were collected at harvest in each field. Soil samples were collected using a standard soil probe to a depth of 16 cm following a zig-zag pattern across the experimental area (1 composite sample comprised of 50 soil plugs per field). Soil nutrients and chemistry was quantified using the Mehlich 3 extraction method (Mehlich, 1984) and reported in the North Carolina Department of Agriculture (NCDA)

Index (Hardy et al., 2008) using Waters Agricultural Laboratories Inc., Camilla, GA. Levels of organic matter and soil texture measurements were also obtained.

Grower interviews were conducted to obtain the previously planted crop (1 year prior) for each field. Weed density ratings were taken immediately prior to harvest by weed scientists. Damage to roots caused by root feeding insects (including white grubs and flea beetles) was evaluated by entomologists from separate root samples taken from the same replications.

Postharvest disease assessment. Roots were evaluated for susceptibility to *R. stolonifer* and *E. chrysanthemi* after 100-105 days in storage. The day before inoculation, roots were hand washed in tap water and allowed to air dry. Each replication (50 roots) was separated into two groups of 20 roots and one group of 10 roots. One 20-root lot was inoculated with *R. stolonifer*, the other set of 20 roots was inoculated with *E. chrysanthemi*, and the remaining set of 10 roots was held at 15.6-18.3 C and served as a non-inoculated control.

The *R. stolonifer* isolate used in this study was originally collected in 1992 from a sweetpotato showing Rhizopus soft rot symptoms and signs and stored on silica crystals at 3 C (Perkins, 1962). To produce inoculum, silica crystals were transferred to potato dextrose agar (Difco, Sparks, MD) and incubated at room temperature (21-22 C) for five days. The plates were washed with a 0.01% octylphenol ethoxylate (Triton™ X-15, Dow, New Jersey) solution and the spores removed by gently rubbing with a bent glass rod. The suspension was filtered through three layers of cheesecloth to remove mycelial fragments and adjusted to a concentration of 10^6 sporangiaspores/mL. The resulting spore suspension was stored at 3 C overnight. On the day of inoculation, roots were wounded on opposite sides of the midsection with an impact wound device which created a consistent wound (8 mm diam × 1 mm deep). The wounds were immediately painted with the spore suspension using a foam brush. After inoculation, roots were placed into ventilated plastic storage crates and stored at 15.6-18.3 C. At 10 days, roots were rated for incidence of Rhizopus soft rot.

The *E. chrysanthemi* isolate used in this study was recovered from a sweetpotato root showing bacterial root rot symptoms. The bacterium was stored on silicia crystals at -12 C until use. One day prior to inoculation, the bacterium was revived by plating the silica crystals onto yeast dextrose carbonate agar (YDCA) and incubating at 30 C for 24 hours. The resulting colony was streaked onto fresh YDCA and incubated at 30 C for 24 hours. On the day of inoculation, the plates were washed with sterile distilled water and the resulting suspension adjusted to 10^8 CFU/mL using a spectrophotometer (0.1 optical density at 620 nm). The roots were inoculated by stabbing the midsection of each root with a disposable plastic pipet filled with 0.05 mL of the bacterial suspension (the pipet was left in place - approximately 1 cm deep into the tissue). The inoculated roots were placed in a ventilated plastic crate and stored at 29.4 C for 10 days after which they were rated for incidence of bacterial soft rot.

With both pathogens, disease incidence was easily assessed because large portions of root tissue were soft and originated at the point of inoculation. Whereas sound roots remained firm, even at the point of inoculation.

Data analysis. Pearson Correlation Coefficients were calculated between incidence of each disease and all predictors (Table 2.1) for the individual years of the study and all three years pooled (PROC CORR; SAS V8, SAS Institute, Cary, NC). Extreme outliers were removed from the dataset (replaced as missing data point) and disease data was averaged over reps within the two insecticide and the two non-insecticide treated replications. An initial model was created using stepwise forward selection to identify important predictors (PROC REG; SAS V8; SAS Institute, Cary, NC) for *E. chrysanth*emi and *R. stolonifer* susceptibility with all fields set as random. Interactions were not included because of the large (153 total) number of potential predictors in the data set. Only those models in which all variables were significant (*p*-value <0.10) were kept for further analysis. Mixed model analysis (PROC MIXED) with fields set as random was carried out between the variables identified in the stepwise selection as potentially important. Final reduced mixed models for each disease were obtained by eliminating predictors one at a time if *p*-value was >0.05.

RESULTS

A wide range in susceptibility to *R. stolonifer* and *E. chrysanthemi* was observed both among fields within a single year and among the years of this study (Figure 2.2). In 2005, a significant decrease in Rhizopus soft rot incidence was seen across all fields as compared to 2004 and 2006. Mean Rhizopus soft rot incidence was 42.5% (standard deviation (SD)=29.6%) in 2004, 12.2% (SD=15.2%) in 2005 and 57.1% (SD=33.1%) in 2006. Mean bacterial root rot was 32.5% (SD=27.4%)in 2004, 50.8% (SD=20.8%) in 2005 and 86.5% (SD=12.6%) in 2006. For the three-year pooled data set, mean Rhizopus soft rot incidence was 34.9% (SD=31.7%) and mean bacterial root rot was 51.0% (SD=30.5%).

A significant correlation (coeff.=0.01840; *p*-value=0.04) was found between *R. stolonifer* susceptibility and *E. chrysanthemi* susceptibility when the three years were pooled. However, examination of the scatterplot of Rhizopus soft rot incidence against bacterial root rot incidence (Figure 2.3) shows a relatively weak relationship.

Pearson correlations of bacterial root rot incidence and Rhizopus soft rot incidence with all variables revealed significant relationships only between soil and weather variables. There was no significant correlation between incidence of either disease and insect injury, weed density or previous year's crop (data not shown) in the individual years of the study or the three-year pooled dataset.

Within the soil fertility and chemistry variables, there were many significant correlations (*p*-value <0.05) to incidence of both Rhizopus soft rot and bacterial root rot (Table 2.2). For Rhizopus soft rot incidence, highly significant negative correlations (*p*-value ≤0.0001) were seen with percent magnesium (Mg) and highly significant positive correlations (*p*-value ≤0.0001) were seen with soil managanese (Mn) and phosphorus (P) indices. For bacterial root rot incidence, highly significant negative correlations (*p*-value ≤0.0001) were seen with percent humic matter (HM) and pH (pH) and highly significant positive correlations (*p*-value ≤0.0001) were seen with soil acidity (Ac), cation exchange capacity (CEC) and copper (Cu), sulfur (S), and zinc (Zn) indices. Soil texture (% sand, silt, or clay) did not significantly correlate to either disease.

Within the weather variables, significant correlations (*p*-value <0.05) were seen for both Rhizopus soft rot and bacterial root rot (Tables 2.3, 2.4 and 2.5). Both diseases showed significant negative correlations to increasing mean air temperature (AT) and soil temperature at both the 2 cm and 4 cm depths (ST_2 and ST_4) in all time periods (7 d, 14 d, 21 d, 28 d pre-harvest and entire growing season) (Table 2.3). Soil moisture levels at 10 cm, 40 cm, and 100 cm depths (SM_{10}, SM_{40}, SM_{100}) in all time periods was significantly correlated (p-value <0.03) for both diseases; however, Rhizopus soft rot susceptibility showed a positive correlation while bacterial root rot showed a negative correlation. These correlations to weather variables were not seen when individual years were analyzed separately (data not shown). This is likely due to a smaller sample size and the strength of the correlation within an individual year.

Exceeding thresholds for high and low air and soil temperature were also significantly correlated to incidence of both diseases (Table 2.4). Increased days in which air temperature dropped below 18ºC (AT-L) as well as when soil temperature dropped below 13ºC at both 2 and 4 cm depths ($ST\text{-}L_2$ and $ST\text{-}L_4$) was positively correlated (p-value ≤0.0017) to both Rhizopus soft rot and bacterial root rot. A differential response was seen to increased days in which soil temperatures exceeded 32ºC at a depth of 2 cm ($ST\text{-}H_2$) with Rhizopus soft rot incidence showing a significant negative correlation at all time periods (p-value ≤0.0151) and bacterial root rot showing a significant positive correlation (p-value≤0.0289) at all time periods except the 7 days pre-harvest. At a depth of 4 cm, there were no days which exceeded the high soil heat threshold ($ST\text{-}H_4$) in the 21 days pre-harvest. The time period of 28 days pre-harvest was not significantly correlated with Rhizopus soft rot. The correlation between days exceeding the high heat threshold over the entire growing season was significant with a negative correlation to Rhizopus soft rot incidence (p-value=0.0005) and a highly significant positive correlation to bacterial root rot (p-value<0.0001).

Significant correlations were also seen to high and low soil moisture thresholds (Table 2.5); with Rhizopus soft rot incidence positively correlated to increased days experiencing high soil moisture at 10, 40, or 100 cm depths (SM-H_{10}, SM-H_{40}, SM-H_{100}) at 21 days and 28 days pre-harvest as well as the entire growing season. Bacterial root rot incidence was negatively correlated (*p*-value<0.0001) to high soil moisture at all depths (SM-H_{10}, SM-H_{40}, SM-H_{100}) in all time periods (7 d, 14 d, 21 d, 28 d pre-harvest and entire growing season). Rhizopus soft rot incidence was correlated to increased number of days of exceeding the low soil moisture threshold at all three depths (SM-L_{10}, SM-L_{40}, SM-L_{100}), while bacterial root rot incidence was not correlated at any depth at any time period.

Stepwise regression followed by mixed model analysis identified significant relationships (*p*-value <0.05) between certain weather and soil parameters and Rhizopus soft rot and bacterial root rot incidence (Table 2.6). The following regression equation describes the relationship of soil and weather variables to the susceptibility of Beauregard sweetpotatoes to Rhizopus soft rot caused by *R. stolonifer*:

$$RSR = 61.91 - 28.3Y04 - 38.70Y05 + 0.13P - 0.93Ca$$
$$- 20.97HM - 149.51AT_{(GS)} + 313.09SM_{40(GS)} + 142.39ST_{2(GS)}$$

where *RSR* is Rhizopus soft rot incidence (%), *Y04* is year 2004, *Y05* is year 2005, *Ca* is the percent of the soil cation exchange capacity (CEC) occupied by calcium measured at harvest, *P* is an index of the amount of plant-available soil phosphorus measured at harvest, *HM* is soil humic matter (%) measured at harvest, $AT_{(GS)}$ is the mean air temperature (ºC) over the growing season, $SM_{40(GS)}$ is the mean volumetric soil moisture (m^3/m^3) at 40 cm over the growing season, and $ST_{2(GS)}$ is the mean soil temperature (ºC) at 2 cm over the growing season. This model is a good fit for predicting Rhizopus soft rot incidence as the correlation between the actual Rhizopus soft rot incidence values and the predicted values was significant (coeff.=0.98314, *p*-value=<0.0001) (Figure 2.4). While this model utilizes the mean for the entire growing season for air temperature, soil moisture and soil temperature variables, the time periods leading to harvest (7 d, 14 d, 21 d, and 28 d pre-harvest) could be substituted for each of these three variables without reducing the significance of the model (data not shown).

The following regression equation describes the relationship of soil and weather variables to the susceptibility of Beauregard sweetpotatoes to bacterial root rot caused by *E. chrysanthemi*:

$$BRR = 229.14 - 40.09Y05 - 36.82Y06 - 16.17pH + 5.05ST\text{-}H_{10(14d)}$$

where BRR is bacterial root rot incidence (%), $Y05$ is year 2005, $Y06$ is year 2006, pH is soil pH measured at harvest, and $ST\text{-}H_{10(14d)}$ is the number of days that soil temperature exceeds 32 (ºC) for any one hour in a 24 hour period in the 14 days prior to harvest. This model is a good fit for predicting bacterial root rot incidence as the correlation between the actual bacterial root rot incidence values and the predicted values was significant (coeff.=0.96886, *p*-value=<0.0001) (Figure 2.5). Unlike the Rhizopus soft rot incidence model, only the use of the 14 days pre-harvest high soil temperature variable ($ST\text{-}H_{10(14d)}$) results in a significant model (the other time periods for high soil temperature – 7, 21, 28 days pre-harvest and growing season – are not interchangeable within the model).

DISCUSSION

Beauregard, the sweetpotato cultivar used in this study, is considered moderately susceptible to infection by *R. stolonifer* (Clark and Hoy, 1994; Holmes and Stange, 2002) and highly susceptible to root rot caused by *E. chrysanthemi* (Clark et al., 1989). Our results, however, demonstrate that susceptibility can vary significantly among fields in a single year, as well as between growing seasons. This study also identifies preharvest soil and weather factors which are related to sweetpotato susceptibility to postharvest Rhizopus soft rot and bacterial root rot.

While many preharvest variables were significantly correlated to increased Rhizopus soft rot and/or bacterial root rot when analyzed individually, a multiple regression model best describes the relationship of soil and weather conditions to postharvest disease susceptibility. Predictive models composed of different variables were significant for each disease (Table 2.6). For Rhizopus soft rot, percent soil humic matter at harvest (HM) has a greater effect on Rhizopus soft rot incidence (parameter estimate of -20.97) than changing levels of the soil phosphorus index (P) or percent calcium (Ca), although all are significant in the model. In this study, the soil samples were taken at harvest to mimic a normal fall sampling time used to predict soil fertility needs for the next season. Therefore, the results of certain nutrients, like soil phosphorus (P), are presented as an index by the soil testing agency. The index serves as a guide for the next season's application needs but not as a measure of the absolute value. The rationale for using a fall soil test, instead of a spring pre-plant soil test, was to develop a predictive model for disease susceptibility that can be used by sweetpotato growers incorporating already utilized techniques. Research is needed to determine the effect of absolute values or specific treatments of nutrients like phosphorus or calcium on the susceptibility of sweetpotatoes to Rhizopus soft rot.

Soil pH levels at harvest (pH), which ranged from 4.6 to 6.5 (μ=5.7) in the fields used in this study, were identified by the mixed model analysis as a significant predictor of bacterial root rot. While low soil pH levels are known to reduce the occurrence of another bacterial disease of sweetpotatoes, soil rot/pox caused by *Streptomyces ipomoea*, soil rot/pox infection occurs in the field with the soil pH levels directly affecting the pathogens ability to induce disease. Low soil pH treatments also affect sweetpotato growth by reducing the marketable yield of cv. Jewel sweetpotatoes (Ristaino and Averre, 1992). We found that higher soil pH levels were correlated with reduced postharvest *E. chrysanthemi* susceptibility and also negatively contributed to the predictive model (when all other factors in the model are considered). Further study is needed to determine the effect of soil pH during the growing season on 'Beauregard' sweetpotato storage root physiology to determine how soil pH is affecting nutrient levels or other root tissue factors which in turn affect postharvest bacterial root rot susceptibility.

The weather variables identified as significant in the model (AT, SM_{40}, and ST_2) have the greatest overall effect on predicting Rhizopus soft rot incidence with SM_{40} (increased soil moisture [m^3/m^3] at 40 cm depth) for the growing season having the largest effect on predicting increased Rhizopus soft rot incidence (parameter estimate=313.09) when all other factors in the model are considered. For all three weather variables, there does not appear to be a specific preharvest time period that is more important to predicting Rhizopus soft rot susceptibility as all time periods analyzed (7 d, 14 d, 21 d, 28 d pre-harvest or entire growing season) were interchangeable within the model (which remained statistically significant). This is not true for the bacterial root rot model; only the use of the weather variable ST-H_2 (increased days of soil temperature exceeding 32ºC at a depth of 2cm) for 14 days pre-harvest resulted in a significant model.

In general, there is limited research data to explain the correlations between environmental conditions during the growing season and postharvest decay susceptibility of sweetpotatoes. A main limiting factor of the published research on this topic is that the specific pathogen is not identified and is only referred to in general terms such as "decay" or "rot". Another complication is that 'Beauregard' is a relatively new cultivar (Rolston et al., 1987) and therefore was not available for earlier studies.

Relationships have been observed between soil moisture and temperature at harvest and postharvest "decay" of sweetpotatoes. A study of the effect of temperature and soil moisture near harvest showed that cv. Porto Rico grown in Louisiana was occasionally more susceptible to postharvest decay (non-inoculated) when harvested from a field that experienced a cold, wet period prior to harvest (Kushman et al., 1954). In a follow-up study, the researchers extended the harvest season into December and confirmed that cold, wet soils decrease sweetpotato quality by increasing internal breakdown (Kushman and Deonier, 1958).

Excessive irrigation treatments increased decay at harvest (Ton and Hernandez, 1978) (averaged over 17-28 sweetpotato cultivars) and during curing and storage (Thompson et al., 1992) in cv. Jewel roots. Thompson et al. (1992) also found a slight increase in decay in cv. Jewel roots receiving the least irrigation water. A field study using 'Jewel' and 'Centennial' sweetpotatoes found that greater losses (due to weight loss and unspecified rot) were experienced with a 3-day flooding period than with a 1- or 2-day flooding period (Corey, et al., 1982).

A growth chamber study confirmed earlier data on flooding (Ahn et al., 1980). Roots grown in warm (24-34°C), water-saturated soils for one week prior to harvest resulted in the most root decay and quality reductions. Less decay was reported in roots grown in cold (4°C), water-saturated soils and the non-saturated soils at either the warm or cold temperatures. The specific pathogens causing the decay were not recorded in any of these studies, but the results suggest that soil moisture levels, soil temperature and flood stress during the growing season are related to postharvest disease susceptibility.

Soil moisture and temperature also affect root morphology and physiology which in turn could affect disease susceptibility. A greenhouse study showed that sweetpotatoes grown under drought stress conditions produce significantly thicker periderm tissue than those grown in a non-drought stressed environment (Harrison, et al., 2006). Villavicencio et al. (2007) studied the effect of three growing temperature regimes on root characteristics such as lignification, periderm adhesion, and pectinase activity. They found a positive correlation between pectinase activity and growth temperature indicating that temperature has an effect on strength of cell wall bonds. The authors also found a positive correlation between periderm lignification and growth temperature indicating that roots grown at higher temperatures are likely to be more resistant to compression type injuries. While not measured in this study, injury resistance could play a role in the disease susceptibility seen in this study.

The use of environmental stress thresholds (e.g., exceeding a threshold set for high soil temperature [ST-H] or low soil moisture [SM-L]) to define the postharvest response of sweetpotatoes (e.g., effect on storability or disease susceptibility) is a relatively new research direction. The thresholds for temperature and soil moisture used in this analysis were defined using preliminary field research results to describe physiological responses of sweetpotatoes to environmental stress. Other values to describe the thresholds (e.g., using a threshold of <12ºC for low air temperature [AT-L] as opposed to <13ºC) were examined in preliminary stages of analysis (data not shown), however, the threshold values used in the final analysis best described this dataset. As the body of research grows, threshold values for environmental stress as affecting sweetpotato physiology will become better defined. However, the predictive models developed for Rhizopus soft rot and bacterial root rot were highly significant using the thresholds as defined in this study.

This study produced a detailed dataset which will be of use for validating disease prediction models using results from future replicated studies. This work represents the first step to developing a weather-based decision system for predicting postharvest disease susceptibility of sweetpotatoes based on preharvest conditions.

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Table 2.1. Potential predictors of Rhizopus soft rot and bacterial root rot incidence recorded for each sweetpotato field location in North Carolina, 2004-2006.

Variable name	Description
Soil[a]	
Sand	Sand (%)
Silt	Silt (%)
Clay	Clay (%)
Ac	Exchangeable acidity (meq/100 cm^3)
CEC	Cation exchange capacity (meq/100 cm^3)
HM	Soil humic matter (%)
pH	Soil pH
Ca	Percent of cation exchange capacity occupied by calcium (%)
Cu	Plant available copper (index)
K	Plant available potassium (index)
Mg	Percent of CEC occupied by magnesium (%)
Mn	Plant available manganese (index)
P	Plant available phosphorus (index)
S	Plant available sulfur (index)
Zn	Plant available zinc (index)
Weather[b]	
AT	Air temperature (ºC)
AT-L	Days of low air temperature[c] (<18ºC)
ST_2, ST_4	Soil temperature (ºC) estimated at 2 and 4 cm depths
$ST\text{-}H_2$, $ST\text{-}H_4$	Days of high soil temperature[c] (>32ºC) estimated at 2 and 4 cm depths
$ST\text{-}L_2$, $ST\text{-}L_4$	Low soil temperature[c] (<13ºC) estimated at 2 and 4 cm depths)
SM_{10}, SM_{40}, SM_{100}	Soil moisture [volumetric water potential (m^3/m^3)] estimated at 10, 40, and 100 cm depths
$SM\text{-}H_{10}$, $SM\text{-}H_{40}$, $SM\text{-}H_{100}$	Days of high soil moisture[c] [volumetric water potential >0.31 (m^3/m^3)] estimated at 10, 40, and 100 cm depths
$SM\text{-}L_{10}$, $SM\text{-}L_{40}$, $SM\text{-}L_{100}$	Days of low soil moisture[c] [volumetric water potential <0.15 (m^3/m^3)] estimated at 10, 40, and 100 cm depths

[a]Soil chemistry and fertility from soil sample taken at harvest was quantified using the North Carolina Department of Agriculture (NCDA) Index (Hardy et al., 2008).
[b]Estimated hourly weather data
[c]A day was recorded as experiencing the predictor when a single hour in the 24-hour period reached or exceeded the defined threshold.

Table 2.2. Relationships of *Erwinia chrysanthemi* and *Rhizopus stolonifer* susceptibility of sweetpotatoes (cv. Beauregard) to soil texture, chemistry and fertility measured at harvest in North Carolina, 2004-2006.

		E. chrysathemi		***R. stolonifer***	
Soil variable[a]	**Mean (Std. dev.)**	**Corr. coef.**[b]	***P* value**	**Corr. coef.**[b]	***P* value**
Texture					
Sand	78.34(8.61)	0.05704	0.3331	-0.09715	0.0981
Silt	7.01(3.51)	-0.02122	0.7189	0.04600	0.4344
Clay	14.66(6.41)	-0.06830	0.2463	0.10548	0.0724
Chemistry					
Acidity (Ac)	1.10(0.44)	0.24546	<0.0001	0.21825	0.0002
Cation exchange capacity (CEC)	4.83(1.66)	0.22432	0.0001	0.11415	0.0517
Humic matter (HM)	1.12(0.53)	-0.22478	0.0001	-0.13988	0.0170
pH	5.72(0.44)	-0.33435	<0.0001	-0.02050	0.7277
Fertility					
Ca	37.82(8.91)	-0.09947	0.0909	-0.09639	0.1008
Cu	84.77(64.01)	0.25297	<0.0001	0.13993	0.0169
K	51.48(24.65)	0.03514	0.5512	-0.22754	<0.0001
Mg	10.38(3.91)	-0.06098	0.3007	-0.10358	0.0777
Mn	64.63(39.01)	0.06566	0.2651	0.27511	<0.0001
P	143.90(67.29)	0.14664	0.0124	0.26100	<0.0001
S	50.19(17.49)	0.36276	<0.0001	-0.10185	0.0828
Zn	117.85(109.47)	0.27244	<0.0001	0.10613	0.0706

[a]Soil parameters are reported using the North Carolina Department of Agriculture (NCDA) Index (Hardy et al., 2008)
[b]Pearson's correlation coefficients were calculated for the pooled data set of 2004, 2005, 2006 (n=75 fields).

Table 2.3. Relationship of *Erwinia chrysanthemi* and *Rhizopus stolonifer* susceptibility of sweetpotatoes (cv. Beauregard) to mean air temperature, soil temperature, and soil moisture in North Carolina, 2004-2006.

		E. chrysanthemi		*R. stolonifer*	
Weather (days prior to harvest)[a]	**Mean (Std. dev.)**	**Corr. coef.[b]**	***P* value**	**Corr. coef.[b]**	***P* value**
AT					
7 d pre-harvest	21.43(3.55)	-0.26506	<0.0001	-0.20966	0.0003
14 d pre-harvest	21.93(2.78)	-0.28865	<0.0001	-0.20747	0.0004
21 d pre-harvest	22.26(2.57)	-0.28210	<0.0001	-0.21346	0.0002
28 d pre-harvest	22.79(2.31)	-0.26184	<0.0001	-0.22131	0.0001
Growing season	25.05(0.80)	-0.12019	0.0408	-0.43154	<0.0001
ST_2					
7 d pre-harvest	22.18(3.76)	-0.28240	<0.0001	-0.20678	0.0004
14 d pre-harvest	22.66(2.92)	-0.30148	<0.0001	-0.21508	0.0002
21 d pre-harvest	23.00(2.66)	-0.29030	<0.0001	-0.2222	0.0001
28 d pre-harvest	23.53(2.38)	-0.27132	<0.0001	-0.22960	<0.0001
Growing season	25.79(0.83)	-0.12053	0.0403	-0.43133	<0.0001
ST_4					
7 d pre-harvest	20.21(3.57)	-0.28226	<0.0001	-0.20830	0.0003
14 d pre-harvest	20.67(2.78)	-0.30157	<0.0001	-0.21804	0.0002
21 d pre-harvest	20.99(2.54)	-0.29041	<0.0001	-0.22442	0.0001
28 d pre-harvest	21.50(2.27)	-0.27120	<0.0001	-0.23138	<0.0001
Growing season	23.65(0.79)	-0.12143	0.0388	-0.43199	<0.0001
SM_{10}					
7 d pre-harvest	0.29(0.04)	-0.40115	<0.0001	0.13034	0.0262
14 d pre-harvest	0.28(0.05)	-0.31198	<0.0001	0.24178	<0.0001
21 d pre-harvest	0.28(0.05)	-0.29912	<0.0001	0.34360	<0.0001
28 d pre-harvest	0.28(0.05)	-0.36247	<0.0001	0.33553	<0.0001
Growing season	0.28(0.03)	-0.32472	<0.0001	0.32046	<0.0001
SM_{40}					
7 d pre-harvest	0.28(0.05)	-0.36726	<0.0001	0.23030	<0.0001
14 d pre-harvest	0.27(0.06)	-0.31348	<0.0001	0.29556	<0.0001
21 d pre-harvest	0.27(0.06)	-0.31613	<0.0001	0.35936	<0.0001
28 d pre-harvest	0.27(0.06)	-0.36265	<0.0001	0.34892	<0.0001
Growing season	0.27(0.03)	-0.29812	<0.0001	0.32199	<0.0001
SM_{100}					
7 d pre-harvest	0.24(0.07)	-0.34001	<0.0001	0.31567	<0.0001
14 d pre-harvest	0.24(0.07)	-0.33921	<0.0001	0.31143	<0.0001
21 d pre-harvest	0.24(0.07)	-0.36820	<0.0001	0.32900	<0.0001
28 d pre-harvest	0.24(0.07)	-0.40077	<0.0001	0.31423	<0.0001
Growing season	0.24(0.04)	-0.29605	<0.0001	0.28691	<0.0001

[a]Parameters were estimated using hourly site specific weather data. Where AT=mean air temperature (ºC), ST_2=mean soil temperature (ºC) at 2 cm depth, ST_4=mean soil temperature (ºC) at 4 cm depth, SM_{10}=mena soil moisture (m^3/m^3) at 10 cm depth, SM_{40}=mean soil moisture (m^3/m^3) at 40 cm depth, and SM_{100}=mean soil moisture (m^3/m^3) at 100 cm depth.

[b]Pearson's correlation coefficients were calculated for the pooled dataset of 2004, 2005, 2006 (n=75 fields).

Table 2.4. Relationships of *Erwinia chrysanthemi* and *Rhizopus stolonifer* susceptibility of sweetpotatoes (cv. Beauregard) to high and low soil and air temperature in North Carolina, 2004-2006.

		E. chrysanthemi		***R. stolonifer***	
Stress parameter[a]	**Mean (std. dev.)**	**Corr. coef.**[b]	***P* value**	**Corr. coef.**[b]	***P* value**
AT-L					
7 d pre-harvest	0.22(0.67)	0.18327	0.0017	0.29094	<0.0001
14 d pre-harvest	0.37(0.99)	0.23870	<0.0001	0.24182	<0.0001
21 d pre-harvest	0.37(0.99)	0.23870	<0.0001	0.24182	<0.0001
28 d pre-harvest	0.37(0.99)	0.23870	<0.0001	0.24182	<0.0001
Growing season	0.39(0.99)	0.32290	<0.0001	0.24182	<0.0001
$ST-H_2$					
7 d pre-harvest	0.52(1.04)	0.03599	0.5416	-0.26292	<0.0001
14 d pre-harvest	0.78(1.33)	0.17851	0.0023	-0.14237	0.0151
21 d pre-harvest	1.37(2.13)	0.12841	0.0288	-0.16240	0.0055
28 d pre-harvest	2.56(3.13)	0.12831	0.0289	-0.15083	0.0100
Growing season	29.56(12.52)	0.34869	<0.0001	-0.35828	<0.0001
$ST-H_4$					
7 d pre-harvest	0	.	.	.	.
14 d pre-harvest	0	.	.	.	.
21 d pre-harvest	0	.	.	.	.
28 d pre-harvest	0.01(0.12)	-0.03034	0.6069	-0.06867	0.2429
Growing season	1.19(1.13)	0.44850	<0.0001	-0.20426	0.0005
$ST-L_2$					
7 d pre-harvest	1.06(1.52)	0.32290	<0.0001	0.20958	0.0003
14 d pre-harvest	1.27(2.05)	0.30165	<0.0001	0.21909	0.0002
21 d pre-harvest	1.67(2.86)	0.30777	<0.0001	0.22323	0.0001
28 d pre-harvest	1.92(3.47)	0.31176	<0.0001	0.23324	<0.0001
Growing season	2.21(3.75)	0.33403	<0.0001	0.21766	0.0002
$ST-L_4$					
7 d pre-harvest	1.03(1.47)	0.27020	<0.0001	0.22279	0.0001
14 d pre-harvest	1.26(2.04)	0.26817	<0.0001	0.23567	<0.0001
21 d pre-harvest	1.62(2.76)	0.27545	<0.0001	0.24189	<0.0001
28 d pre-harvest	1.84(3.31)	0.28010	<0.0001	0.24682	<0.0001
Growing season	2.06(3.60)	0.30680	<0.0001	0.24077	<0.0001

[a]Parameters were estimated using site specific weather data and thresholds were calculated as the number of days when the defined threshold was exceeded for any hour of the day. Where AT-L=Air temperature <18ºC, $ST-H_2$=soil temperature >32ºC at 2cm, $ST-H_4$=soil temperature >32ºC at 4 cm, $ST-L_2$=soil temperature <13ºC at 2 cm, and $ST-L_4$=soil temperature <13ºC at 4 cm

[b]Pearson's correlation coefficients were calculated for the pooled dataset of 2004, 2005, 2006 (n=75 fields).

Table 2.5. Relationships of *Erwinia chrysanthemi* and *Rhizopus stolonifer* susceptibility of sweetpotatoes (cv. Beauregard) to high and low soil moisture in North Carolina, 2004-2006.

		E. chrysanthemi		***R. stolonifer***	
Soil parameter[a]	**Mean (std. dev.)**	**Corr. coef.**[b]	***P* value**	**Corr. coef.**[b]	***P* value**
$SM\text{-}H_{10}$					
7 d pre-harvest	3.29(2.52)	-0.35811	<0.0001	0.09279	0.1142
14 d pre-harvest	6.30(4.70)	-0.41359	<0.0001	0.06401	0.2764
21 d pre-harvest	9.23(6.78)	-0.40898	<0.0001	0.20472	0.0004
28 d pre-harvest	11.97(9.17)	-0.46700	<0.0001	0.22140	0.0001
Growing season	46.84(23.90)	-0.39537	<0.0001	0.25405	<0.0001
$SM\text{-}H_{40}$					
7 d pre-harvest	2.53(3.03)	-0.35117	<0.0001	0.13104	0.0254
14 d pre-harvest	4.99(5.50)	-0.38548	<0.0001	0.09269	0.1146
21 d pre-harvest	7.32(7.56)	-0.42400	<0.0001	0.18160	0.0019
28 d pre-harvest	9.26(9.90)	-0.49245	<0.0001	0.19046	0.0011
Growing season	26.60(21.33)	-0.36080	<0.0001	0.22798	<0.0001
$SM\text{-}H_{100}$					
7 d pre-harvest	1.62(2.75)	-0.31145	<0.0001	0.10886	0.0637
14 d pre-harvest	3.27(5.16)	-0.31419	<0.0001	0.10306	0.0792
21 d pre-harvest	4.73(7.22)	-0.38593	<0.0001	0.14141	0.0158
28 d pre-harvest	5.96(9.08)	-0.43863	<0.0001	0.17849	0.0022
Growing season	11.23(14.67)	-0.41696	<0.0001	0.19848	0.0007
$SM\text{-}L_{10}$					
7 d pre-harvest	0.06(0.47)	0.08057	0.1712	0.03428	0.5602
14 d pre-harvest	0.41(1.23)	0.00592	0.9201	-0.26111	<0.0001
21 d pre-harvest	0.74(2.12)	0.05396	0.3598	-0.30758	<0.0001
28 d pre-harvest	0.79(2.28)	0.05489	0.3516	-0.30730	<0.0001
Growing season	1.70(4.98)	-0.00241	0.9675	-0.32584	<0.0001
$SM\text{-}L_{40}$					
7 d pre-harvest	0.07(0.38)	0.01722	0.7733	-0.02758	0.6394
14 d pre-harvest	0.64(1.92)	-0.02562	0.6639	-0.29478	<0.0001
21 d pre-harvest	1.12(3.18)	0.00804	0.8916	-0.32883	<0.0001
28 d pre-harvest	1.67(4.75)	0.00353	0.9522	-0.30942	<0.0001
Growing season	3.12(9.37)	-0.00140	0.9811	-0.30274	<0.0001
$SM\text{-}L_{100}$					
7 d pre-harvest	1.01(2.37)	0.05495	0.3511	-0.34803	<0.0001
14 d pre-harvest	1.82(4.43)	0.02605	0.6586	-0.35111	<0.0001
21 d pre-harvest	2.69(6.55)	0.01780	0.7627	-0.33488	<0.0001
28 d pre-harvest	3.49(8.38)	0.01924	0.7443	-0.31300	<0.0001
Growing season	6.36(16.37)	0.03422	0.5617	-0.31615	<0.0001

[a]Parameters were estimated using site specific weather data. Calculated as the number of days when the defined threshold was exceeded for any hour of the day. Where $SM\text{-}H_{10}$= soil moisture >0.31 (m^3/m^3) at 10 cm, $SM\text{-}H_{40}$=soil moisture >0.31 (m^3/m^3) at 40 cm, $SM\text{-}H_{100}$=soil moisture >0.31 (m^3/m^3) at 100 cm, $SM\text{-}L_{10}$= soil moisture <0.15 (m^3/m^3) at 10 cm, $SM\text{-}L_{40}$= soil moisture <0.15 (m^3/m^3) at 40 cm, and $SM\text{-}L_{100}$= soil moisture <0.15 (m^3/m^3) at 100 cm

[b]Pearson's correlation coefficients were calculated for the pooled data set of 2004, 2005, 2006 (n=75 fields).

Table 2.6. Final reduced models selected by stepwise regression followed by mixed model analysis to explain the postharvest susceptibility of sweetpotatoes (cv. Beauregard) to *Rhizopus stolonifer* and *Erwinia chrysanthemi* using weather and soil parameters.

Pathogen	Parameter[a]	Parameter estimate	Error	df	t value	*P* value
R. stolonifer						
	Intercept	61.91	146.61	53.4	0.42	0.6745
	Year2004	-28.28	8.68	53	-3.26	0.0020
	Year2005	-38.70	12.67	53	-3.05	0.0035
	Insecticide	-2.48	1.41	60.2	-1.77	0.0825
	P	0.13	0.05	53	2.58	0.0126
	Ca	-0.93	0.37	53	-2.50	0.0156
	HM	-20.97	7.22	53	-2.91	0.0053
	Growing season AT	-149.51	62.20	53	-2.40	0.0198
	Growing season SM_{40}	313.09	132.11	53	2.37	0.0215
	Growing season ST_2	143.39	61.24	53	2.34	0.0230
E. chrysanthemi						
	Intercept	229.14	42.39	56	5.41	<0.0001
	Year2004	-40.09	8.69	56	-4.61	<0.0001
	Year2005	-36.82	7.50	56	-4.91	<0.0001
	Insecticide	-0.48	1.76	61	-0.27	0.7875
	pH	-16.17	5.78	57	-2.80	0.0070
	14 d pre-harvest $ST\text{-}H_2$	5.05	1.79	57	2.83	0.0065

[a]Where Insecticide=insecticide treated compared to non-insecticide treated beds within a field, P=soil phosphorus index, Ca=soil calcium (%), HM=humic matter (%), growing season AT=mean air temperature (ºC) over the growing season, Growing season SM_{40}=mean soil moisture (m^3/m^3) at 40 cm depth over the growing season, Growing season ST_2=mean soil temperature (ºC) at 2 cm depth over the growing season, pH=soil pH, and 14 d pre-harvest $ST\text{-}H_2$=numbers of days exceeding a soil temperature threshold of >32ºC at a depth of 2 cm in the fourteen days prior to harvest.

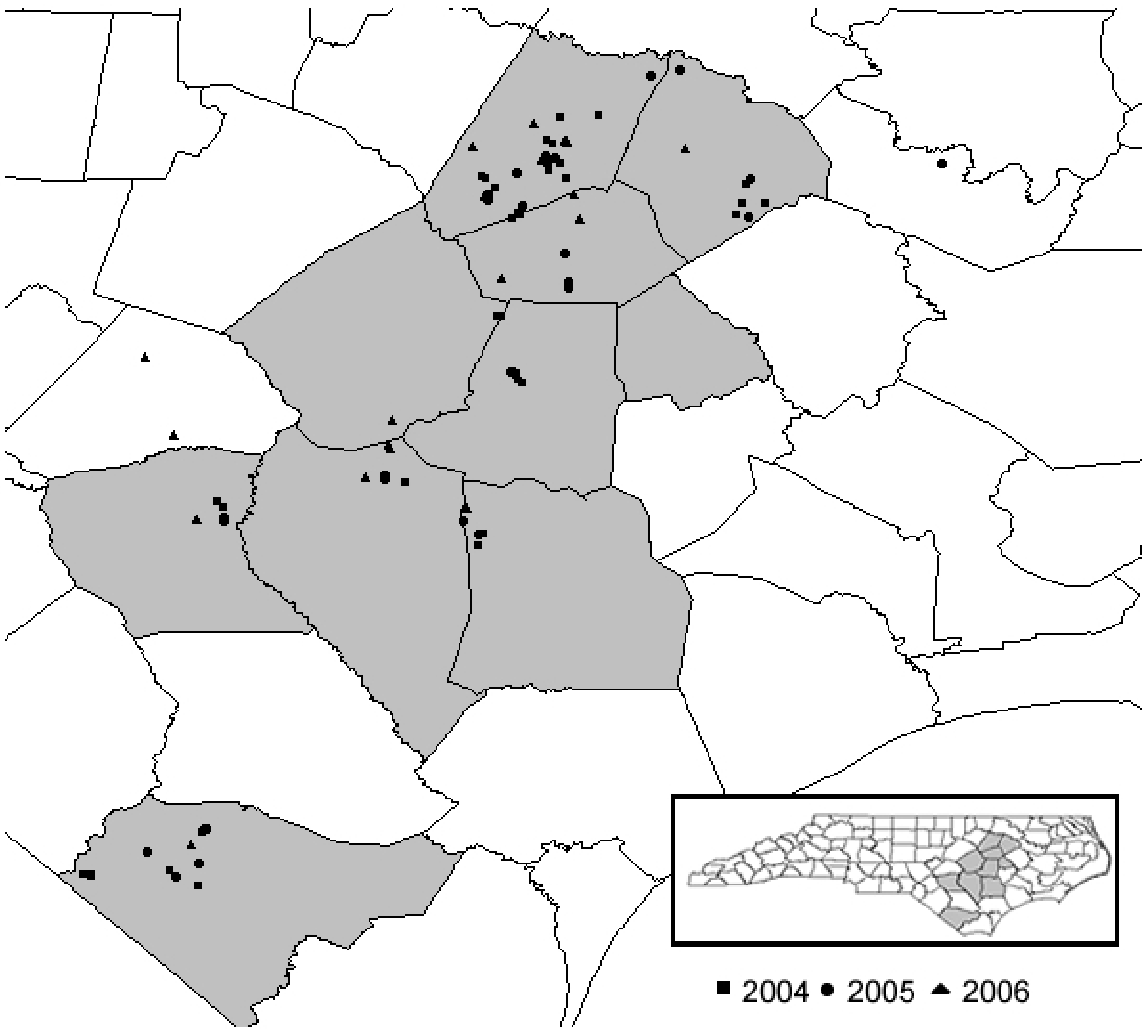

Figure 2.1. Location of sweetpotato fields sampled in North Carolina, 2005-2007. The top sweetpotato producing counties (2005) are highlighted in gray.

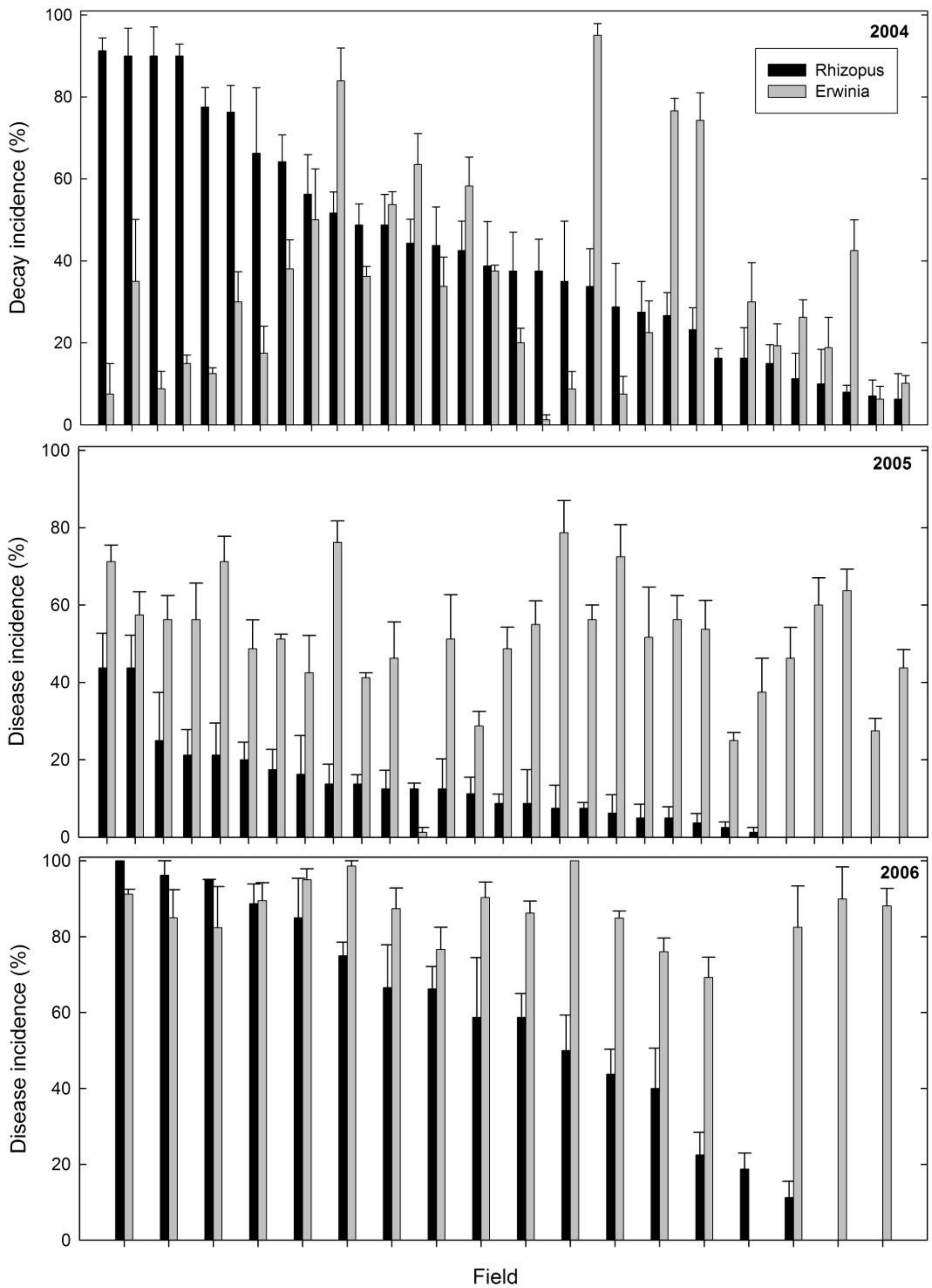

Figure 2.2. Postharvest susceptibility of sweetpotatoes to *Rhizopus stolonifer* and *Erwinia chrysanthemi* in North Carolina in 2004, 2005, and 2006. Each set of paired bars represents a single field and is sorted in descending order for Rhizopus soft rot incidence (left to right).

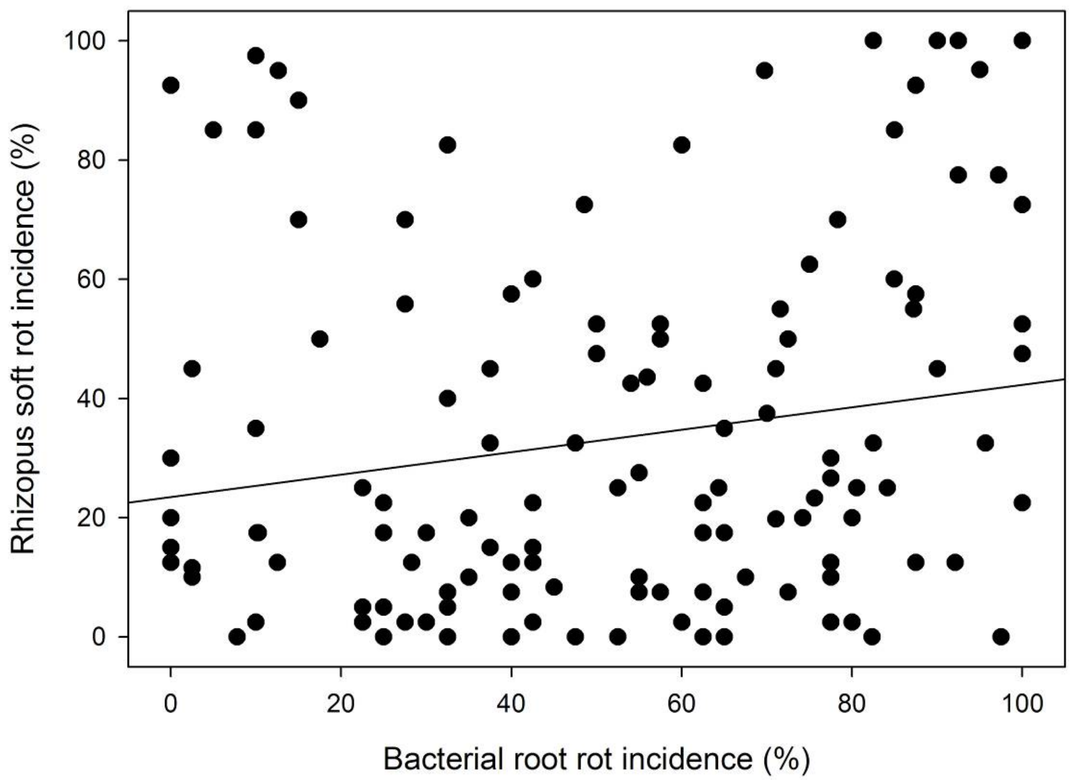

Figure 2.3. Correlation (coeff.=0.01840; *p*-value=0.04) between bacterial root rot incidence and Rhizopus soft rot incidence of sweetpotatoes (cv. Beauregard) in North Carolina, 2004-2006.

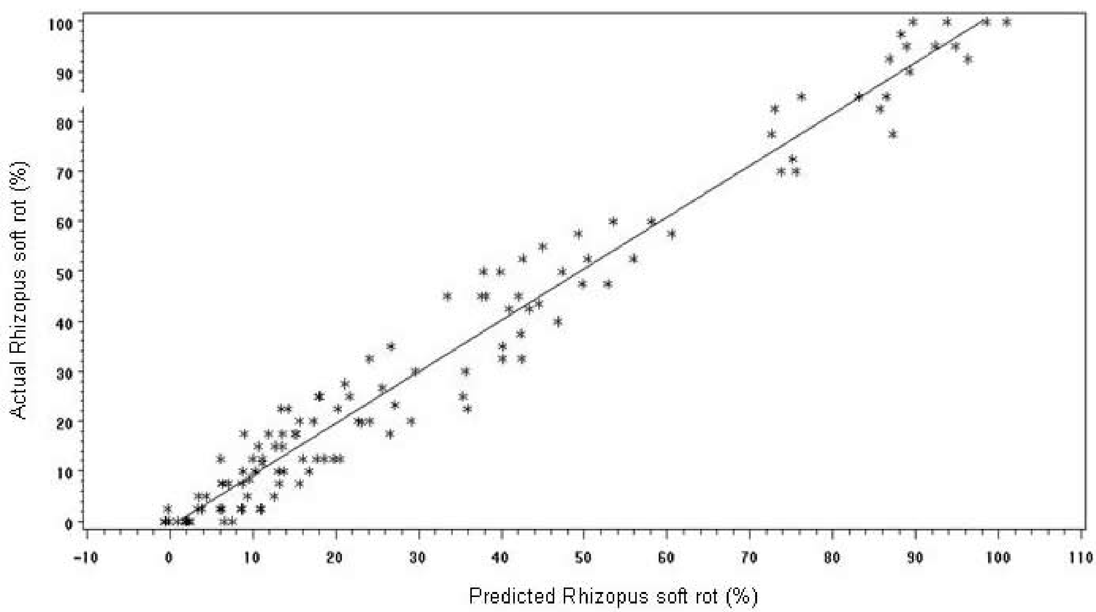

Figure 2.4. Predicted versus actual Rhizopus soft rot incidence (%) using the final reduced mixed model which includes weather and soil parameters.

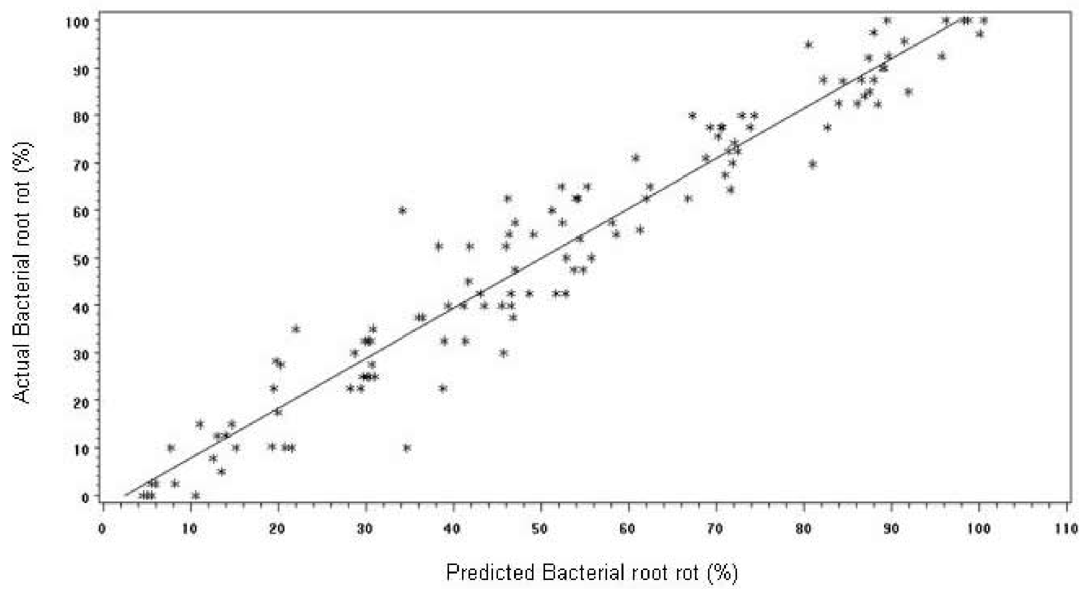

Figure 2.5. Predicted versus actual bacterial root rot incidence (%) using the final reduced mixed model which includes weather and soil parameters.

CHAPTER 3. SUSCEPTIBILITY OF SWEETPOTATOES (*IPOMOEA BATATAS* LAM.) TO DECAY BY *RHIZOPUS STOLONIFER* AS RELATED TO INJURIES OCCURRING ON PACKINGLINES

The following chapter is in preparation for submission to the journal Postharvest Biology and Technology with authors B.A. Edmunds, G.J. Holmes, and C.A. Clark[1]. ([1]Department of Plant Pathology and Crop Physiology, Louisiana State University, Baton Rouge, LA)

Abstract:

Postharvest handling and packing of sweetpotatoes (*Ipomoea batatas* Lam.) can result in increased susceptibility to the wound-obligate pathogen, *Rhizopus stolonifer*, however the relationship is not well understood. The impact forces occurring on forty sweetpotato packinglines in Louisiana and North Carolina were quantified using an impact recording device. A wide range in impact forces was found among packinglines in each state and a relationship was seen between packinglines with increased transfer points having higher cumulative impact forces than packinglines with fewer transfer points. Studies were conducted to understand the relationship between impact forces occurring on packinglines and susceptibility to Rhizopus soft rot. Two sweetpotato cultivars (Hernandez and Beauregard) were injured by dropping in two orientations (root end or root midsection held parallel to the impact surface) from five heights corresponding to impact forces in the range of those measured on commercial packinglines. After dropping, the roots were dip-inoculated in a *R. stolonifer* sporangiospore suspension. In both cultivars, impacts on the

root end resulted in greater decay than the same impact force on the root midsection. Hernandez was significantly more susceptible to Rhizopus soft rot than Beauregard at all impact forces. A separate experiment was conducted to study the cumulative effect of roots passing over a packingline transfer point. Results indicate that increasing the number of times roots are passed over a packingline transfer point results in increased Rhizopus soft rot incidence in both Hernandez and Beauregard. Hernandez was again significantly more susceptible than Beauregard. To confirm that packingline impacts are related to Rhizopus soft rot development, Beauregard roots were sampled from multiple locations along six commercial packinglines in North Carolina. Two replications were artificially inoculated with a *R. stolonifer* sporangiospore suspension and two replications were not inoculated. High decay in the inoculated roots as compared to the non-inoculated roots indicates that wounding occurred on packinglines that resulted in increased disease incidence when the pathogen was present at high levels.

3.1. Introduction

Rhizopus soft rot, caused by the fungus *Rhizopus stolonifer*, is the most common and destructive post-packing disease of sweetpotatoes (*Ipomoea batatas* Lam.) (Clark and Moyer, 1988). Losses due to Rhizopus soft rot can be significant. An estimated 2% of sweetpotatoes are lost to Rhizopus soft rot by the time they reach the retail market (Ceponis and Butterfield, 1974), but losses are sporadic and it takes few rotted roots to cause shipments to be rejected.

Rhizopus soft rot most commonly occurs at harvest and after roots are passed over a packingline to be washed, graded, and boxed. Sweetpotato packinglines are not a level surface but consist of overlapping components or transfer points. These transfer points create height differentials in which roots fall or roll down slopes onto the next component.

Root injuries are a critical factor for the development of Rhizopus soft rot. *R. stolonifer* does not cause disease on undamaged sweetpotato roots but requires an injury for infection to occur (Lauritzen, 1935). When *R. stolonifer* spores (which are ubiquitous in the environment) land in an injury on a susceptible sweetpotato, they very quickly germinate to form mycelia and produce pectolytic enzymes which break down cell walls resulting in a very soft, watery rot (Lauritzen, 1935; Srivastava and Walker, 1959). Root decay can occur in as little as 3 days.

Sweetpotatoes are known to incur three types of injuries during the packing process: skinning, when the periderm is sloughed off; broken ends, when the long, thin root tips are broken off; and bruising, when the root tissue is crushed from bounces and drops on packingline surfaces. *R. stolonifer* infections are more likely to occur with bruise injuries than with smooth injuries (like those caused by skinning and broken ends). Lauritzen (1935) and Srivastava and Walker (1959) found increased Rhizopus soft rot in roots bruised by manually impacting roots on the edge of a hard object or crushing the root tips as compared to smooth cuts. Clark and Hoy (1994) found that puncturing roots with a *R. stolonifer* sporangiospore coated screw resulted in higher Rhizopus soft rot than roots injured in a free fall drop of 1m onto a flat surface. Holmes and Stange (2002) again found that bruises were more susceptible than scrapes or punctures. A limitation of these studies is that puncture wounds are rare in commercial packing settings and the impact force required to initiate bruising and subsequent decay was not quantified, making direct comparisons to injuries received on packinglines difficult.

The relationship between impacts occurring on sweetpotato packinglines and the occurrence of root injuries is not well understood. The development of Rhizopus soft rot during shipping suggests that bruising is happening on packinglines to a degree that disease can develop. The impact forces that sweetpotatoes are subjected to during packing are unknown as studies have not been completed to quantify these impact forces.

The objectives of this study were to 1) characterize the impact forces occurring on commercial sweetpotato packinglines using an impact recording device; 2) determine the potential for packingline impacts to result in Rhizopus decay; and 3) confirm that handling on commercial packinglines increases susceptibility to Rhizopus soft rot. These experiments represent the first steps toward defining the relationship between impact forces occurring on packinglines and Rhizopus soft rot development in sweetpotatoes.

3.2. Methods

3.2.1. Measurement of impact forces occurring on sweetpotato packinglines

Impact recording devices (Sensor Wireless, PEI, Canada) were used to measure impact forces occurring on 17 North Carolina and 23 Louisiana sweetpotato packinglines in 2005 and 2006. Two identical impact recording devices were used, one in each state, and were purchased at the same time. Each device was calibrated by the manufacturer prior to use. The impact recording device is comprised of three parts; an accelerometer which measures impact force, a urethane casing which fits tightly around the accelerometer, and a personal digital assistant (PDA) connected to a wireless radio sled. The company-supplied, potato-shaped casing proved inadequate in preliminary trials as the dimensions and buoyancy characteristics did not accurately mimic the behavior of a sweetpotato. To address these issues, a sweetpotato shaped casing was designed with SolidWorks 3D CAD (Concord, MA). A standard shaped US #1 grade sweetpotato root was used as the basis of a three dimensional mold. This mold was then used to produce two identical silicon casings with foamcore-filled pockets added to each end to increase buoyancy (Figure 3.1). The casing halves fit tightly around the accelerometer and the device is the exact shape and buoyancy of a typical U.S. #1 grade sweetpotato. The final specifications of the modified impact recording device (new casing fitted on the accelerometer) were 17.2 cm in length, 7 cm in diameter at the midsection, and a weight of 0.39 kg.

Impact forces (measured as force of deceleration, m/s^2; 9.81 m/s^2 = 1 *g* [gravitational force]) were measured three to five times for all transfer points on each packingline. The impact surface for each transfer point and the height of the drop were recorded. The cumulative impact force was calculated for each packingline by adding the mean maximum impact force for each transfer point.

3.2.2. Inoculum production

The *R. stolonifer* isolate used in these trials was originally collected in 1992 from a sweetpotato showing Rhizopus soft rot symptoms and signs and stored on silica crystals at

3ºC (Perkins, 1962). To produce inoculum, silica crystals were transferred to Petri dishes containing potato dextrose agar (Difco; Sparks, MD) and held at room temperature (22°C) to induce production of sporangiospores. After six days, approximately 10mL of sterile water was added to each plate and the sporangiospores were dislodged by gently rubbing the surface with a bent glass rod. The resulting suspension was filtered through four layers of cheesecloth to remove mycelial fragments and agar pieces. The spore suspension was diluted with 0.01% octylphenol ethoxylate (Triton™ X-15, Dow, New Jersey) to a concentration of 10^6 sporangiospores/ml to reduce clumping. The suspension was kept refrigerated (1°C) overnight. Fresh spore suspension was prepared for each experiment.

3.2.3. Sweetpotato cultivars

Two sweetpotato cultivars were used, Hernandez and Beauregard. Sweetpotatoes were grown according to standard practices in North Carolina. After harvest, the roots were cured and stored in commercial storage facilities. One week prior to experiments, the roots were collected into ventilated plastic crates and transported to an on-site storage room (14.5 ºC/95% relative humidity [RH]). The roots were held at 14.5 C until use. One day prior to the experiment, the roots were gently hand-washed in tap water to remove clinging soil and allowed to air dry. All roots conformed to the US No. 1 grade; average weight was 0.51 kg, average length was 18 cm.

3.2.4. The effect of drop height and root orientation on Rhizopus soft rot development

Two experiments were conducted to study the effect of drop height and root orientation on the development of Rhizopus soft rot. In the first experiment, roots were held parallel to a stainless steel impact surface (root midsection impacted). Consistent drop height was accomplished using a vacuum suction device similar to that described in Menesatti *et al*. (1999). A single root was placed into the vacuum suction cup with the root parallel to the impact surface, raised to the designated drop height, and then the suction manually released, allowing the root to fall. Roots were not allowed to bounce upon impact (roots were caught by hand after first impact). In the second experiment, roots were held perpendicular to the impact surface (root end impacted) and then dropped in a manner similar to the first experiment.

Immediately after dropping, the root was inoculated by submersion in a *R. stolonifer* sporangiospore suspension (prepared as described in section 2.2) for 30 seconds. Inoculated roots were placed in ventilated plastic storage crates and stored at 14.5 C and 95% RH. After 7 days, the roots were rated for incidence of Rhizopus soft rot.

Two cultivars were tested; Hernandez and Beauregard (described in section 2.3). Five drop height treatments were tested (0, 2.5, 5, 23, and 33 cm) which corresponded to maximum impact forces of 0, 98.1, 196.2, 392.4, and 588.6 m/s^2, respectively (as measured with the impact recording device described in section 2.1). The drop height was measured from the bottom of the root. Four replications of 10 roots each were tested for each drop height treatment. The experiments were repeated twice.

3.2.5. Determination of the cumulative effect of packingline transfer points on Rhizopus soft rot development

An experiment was conducted to study the effect of roots passing over a simulated packingline transfer point one or more times on the development of Rhizopus soft rot. The packingline drop used in this experiment consisted of two conveyors running in tandem. The upper conveyor was composed of 5.1 cm wooden rollers and the lower conveyor was a steel supported belt conveyor (0.6 cm non-padded plastic belt). Both conveyors were traveling at a speed of 0.25 m/s and were separated by a vertical drop of 30 cm. The drop treatment was applied by placing 15 roots by hand onto the stopped upper conveyor with the roots orientated parallel to the drop. The conveyors were turned on and the roots were allowed to fall onto the lower conveyor. The conveyors were stopped after all 15 roots had fallen onto the lower conveyor. This constituted a single drop. If the treatment designated additional drops, the roots were moved by hand to the upper conveyor and the process repeated.

The experiment was set up as a 2 x 4 x 4 factorial (2 cultivars x 4 drop treatments x 4 replications). Two cultivars were tested, Beauregard and Hernandez, as described in section 2.3. Four drop treatments were tested; 0, 1, 5, or 10 drops which corresponded to a cumulative impact force of 0, 294, 1471, and 2943 m/s^2 as measured with the impact recording device. There were four replications of 15 roots and the experiment was repeated twice.

Immediately after the drop treatment, the replications were inoculated by submerging the roots in a *R. stolonifer* sporangiospore suspension (prepared as described in section 2.2) for 30 seconds. Inoculated roots were placed in ventilated plastic storage crates and stored at

15 C and 95% RH. After 7 days, the replications were rated for incidence of Rhizopus soft rot.

3.2.6. Potential for Rhizopus soft rot development on commercial packinglines

Commercial sweetpotato packinglines were sampled to determine the effect of packingline impacts on the incidence of Rhizopus soft rot. Six packinglines in North Carolina were sampled on three dates during the 2005-2006 season. The packinglines selected for this experiment contain the types and numbers of transfer points as found in the majority of packinglines surveyed as described in section 2.1. The roots sampled in this experiment differ from those used in previously described experiments (section 2.3.). Specifically cv. Beauregard roots were sampled and roots at each sample date on each packingline originated from a different grower and field, for a total of 18 different fields of Beauregard roots tested.

On each packingline, five sample points were identified that were representative of the entire packing process (i.e., from storage bins to packed cartons). During normal packing operations, 160 U.S. No. 1 grade roots were removed by hand at each designated sample point. The roots from a single sample point were randomly divided into four replications of 40 roots each. Two replications were inoculated by submerging the roots for 30 sec in a 10^6 *R. stolonifer* spore suspension (prepared as described in section 2.2.). The remaining two replications were not inoculated. Replications were placed in separate ventilated plastic crates, transported to a storage facility and stored at 15 C and 90% RH. After seven days, all four replications were rated for incidence of Rhizopus soft rot.

At each sampling time, impacts occurring on the packingline were measured using the impact recording device as described in section 2.1. The impact recording device was passed over each packingline three times and the maximum impact force for individual drops was recorded. Cumulative impact forces for each packingline were calculated by adding the maximum mean impact force of all transfer points.

3.2.7. Statistical analysis

Non-transformed data from the packingline impact survey were subjected to analysis of variance (PROC GLM, SAS Institute, Cary, NC) and Student-Neuman-Kuels means separation tests were performed on the data.

Non-transformed data from impact force vs. root orientation experiments were subject to analysis of variance (PROC ANOVA, SAS Institute, Cary, NC). Data from the two experiments were pooled after testing the error means square for homogeneity. Least significant difference (LSD) values for treatment effects were calculated.

Non-transformed data from the cumulative effect of a single impact was subject to analysis of variance (PROC ANOVA, SAS Institute, Cary, NC). Least significant difference (LSD) values for treatment effects were calculated.

Non-transformed data from the commercial packingline sampling study were subjected to analysis of variance (PROC GLM, SAS Institute, Cary, NC) and Student-Neuman-Kuels means separation tests were performed on the data.

3.3. Results

3.3.1. Impacts occurring on sweetpotato packinglines.

Packinglines in Louisiana and North Carolina differed in the number of transfer points, the types of impact surfaces, and the impact force onto impact surfaces. Three types of equipment (impact surfaces) were only found on North Carolina packinglines; electronic sizers (metal), sponge rolls (sponge covered rollers), and metal plates (stainless steel). These additional types of equipment contributed to the increased number of transitions and cumulative impacts seen on North Carolina packinglines. There were significantly more transfer points on North Carolina packinglines than on Louisiana packinglines (mean 10.6 and 8.5 transfer points, respectively; p=0.016).

There were some significant differences among maximum impact forces on impact surfaces in each state (p<0.001) (Table 3.1). In Louisiana, maximum impacts were significantly lower onto plate-supported conveyors and significantly higher into water in dump tanks than in North Carolina (Table 3.1). Otherwise, there was no difference between maximum impacts occurring on specific impact surfaces in each state. The majority of impact surfaces showed maximum impact forces exceeding 294 m/s^2 and several surfaces exceeded 588 m/s^2 (Table 3.1).

The average cumulative impact forces were not significantly higher in North Carolina (mean=986 m/s^2) than in Louisiana (mean=808 m/s^2). Overall, a wide range in cumulative impacts was seen in both states and was dependent on the number of transfer points; packinglines with more transfer points were more likely to have higher cumulative impacts.

3.3.2. The relationship of impact orientation to R. stolonifer susceptibility

Results of the impact orientation experiments reveal significant differences in cultivar response to increasing drop height and root orientation (Figure 3.2). Differences in the amount of decay were seen between 'Hernandez' and 'Beauregard' when the roots were dropped on the midsection (Figure 3.2A). Hernandez developed decay at all drop heights tested and significant differences were seen between the drop heights. There was no significant difference between the control of 0 m/s^2 (0 cm) and the 98 m/s^2 (2.5 cm) and 196 m/s^2 (5 cm) drops onto the midsection in Beauregard roots with decay incidences of 0%, 0%, and 0.8%, respectively.

When roots were dropped onto root ends, significant differences in Rhizopus soft rot incidence were seen between the two cultivars (Figure 3.2B). Hernanadez developed decay at all drop heights tested. Increasing the drop height resulted in increased decay incidence, but there was no significant difference between the 392 m/s^2 (23 cm) and the 588 m/s^2 (33 cm) drop treatments. In Beauregard, no significant difference was seen between the control of 0 m/s^2 (0cm) and the 98 m/s^2 (2.5 cm) drop onto the root end as decay was 0% in both drop treatments.

Overall, Beauregard was less susceptible than Hernandez when the roots were dropped from the same heights, regardless of root orientation when dropped. Both cultivars showed a significant linear relationship to increasing impact forces occurring at both impact orientations as indicated by high R^2 values (Figure 3.2).

3.3.3. Relationship of multiple packingline drops to R. stolonifer susceptibility

Results of the multiple packingline drop experiment show that a single drop of 294 m/s^2 (30 cm) resulted in a significant increase in decay incidence in Hernandez sweetpotatoes as compared to the non-dropped control (Figure 3.3). In Beauregard, decay incidence after the single drop treatment (cumulative impact of 294 m/s^2) was not significantly different than the non-dropped control. In both cultivars multiple drops resulted in increased decay incidence, however, Hernandez was significantly more susceptible than Beauregard. In Hernandez, the 10 drop treatment (cumulative impact of 2943 m/s^2) resulted in 100% decay incidence while only 14.5% incidence was seen in Beauregard roots.

3.3.4. Potential for Rhizopus soft rot development on commercial packinglines

Roots sampled from commercial packinglines showed very low levels (<0.5%) of naturally occurring Rhizopus soft rot regardless of sample location or packingline sampled (Figure 3.4). Samples taken from the storage bins (the first sample location on all packinglines) showed no significant difference between the inoculated (mean incidence=0.6%) and non-inoculated samples (mean incidence=0%). These roots were transported out of the storage facility but not yet placed onto the packingline (minimal handling). Once roots were added to the packingline, decay incidence was significantly greater in inoculated roots than in non-inoculated roots at 15 of 23 sample locations (not including the first sample location).

Although decay incidence was higher in inoculated roots at the last sample point (packed cartons) as compared to the first sample point (storage bins), a significant linear relationship was not seen. We also did not see a significant difference in decay incidence from the last sample point (packed cartons) among the six packinglines, although the final cumulative impact level differed widely between packinglines (1200-3000 m/s^2 was accumulated by box fill).

3.4. Discussion

Our use of a sweetpotato-shaped impact recording device to quantify packingline impacts is unique. In the early 1990's, sweetpotato packinglines were measured using a first generation, spherical-shaped impact recording device; however, this data was never published (M. Boyette, personal communication). Spherical-shaped impact recording devices have been utilized to study the relationship of packing processes to bruising and surface scuffing in citrus and onion (Miller and Wagner, 1991; Hyde et al., 1992; Shellie, 1997; Bajema and Hyde, 1995). A limitation of a spherical shaped device is that it behaves differently on a packingline than an oblong shaped commodity such as cucumber, potato, carrot or sweetpotato. Second generation impact recording devices with oblong shaped casings were developed for more accurately measuring impacts occurring during potato harvesting and packing (Tennes et al., 1990; Canneyt et al., 2003; Sensor Wireless, Charlottetown, PE, Canada). More recently, an accelerometer was developed that can be placed inside a hollowed out carrot which is then passed over a packingline (Geyer et al., 2006). Using an actual carrot as an accelerometer casing more closely mimics the physical properties of a carrot. However, a new vegetable specimen must be used at each sample date which can introduce excessive variability into the measurements. The shape and consistency of the silicon accelerometer casing used in this study resulted in precise and consistent measurements while accurately mimicking the mechanical behavior of sweetpotatoes during the packing process.

Surveying packinglines and using the sweetpotato shaped impact recording device to quantify impacts identified similarities in the types of components and associated impact forces among sweetpotato packinglines in Louisiana and North Carolina. Packinglines in both states contained the same basic types of components used to wash, grade, and package roots. North Carolina packinglines had several additional, unique components including electronic sizers, metal plates, and sponge-covered rollers (used to wick excess moisture from the roots).

As the packingline impact force data shows, sweetpotatoes are exposed to a wide range of impact forces during the packing process. Although it is well established that Rhizopus soft rot of sweetpotatoes is dependent on root injuries (Lauritzen, 1935; Srivastava and Walker, 1959; Holmes and Stange, 2002), this is the first study to quantify the impact forces occurring during normal packing processes and directly relate those impact forces to disease susceptibility. We have identified an effect of root orientation on susceptibility, with root ends being more susceptible than the root midsection when the same impact force is applied. This is not surprising, as the impacted area is much smaller on root ends. We found a significant linear relationship between increasing impact forces and decay incidence in both cultivars and at both drop orientations. Beauregard roots were not susceptible at the impact force of 100 m/s^2 when dropped on either the end or midsection. This is a significant finding that can lead to changes in packingline design to minimize impact forces.

This work also demonstrates differences in cultivar response to *R. stolonifer* infection. The increased susceptibility to Rhizopus soft rot of Hernandez as compared to Beauregard is well-known (Clark and Hoy, 1994; Holmes and Stange, 2002); however, the differential response of the cultivars to impact forces was not previously characterized. The results of our controlled drop experiments showed Hernandez to be more susceptible at every impact force and orientation combination. These results indicate that Hernandez may always need a preventative fungicide application on packinglines for Rhizopus soft rot control.

The mechanism of resistance among sweetpotato cultivars to damage by impact forces is a research area that needs further exploration. Clark and Hoy (1994) suggested that sweetpotatoes may have two types of resistance, tissue resistance and wounding resistance. It is possible that increased intercellular space in the root tissue of Hernandez allows this cultivar to deform or bruise more extensively during handling (Wright et al., 1968) or that root tissue firmness is a factor in injury severity although this was not measured in this study.

When Beauregard roots were sampled from commercial packinglines, increased decay was seen in the artificially inoculated roots compared to non-inoculated roots from the same sample location. However, on all packinglines at all sampling dates, roots from the end of the packingline (sampled from a packed box) had significantly more decay than the control samples (roots sampled directly from storage). This increased decay incidence indicates that injuries are occurring which are capable of resulting in *Rhizopus* infection. If *R. stolonifer* sporangiospores were present at higher concentration (e.g. because of improper sanitation, sporulating roots from storage added to the packingline, etc.), increased decay incidence would likely occur, especially if the cultivar is more susceptible.

All of the packinglines sampled applied dicloran, a fungicide with efficacy against *R. stolonifer*, at one point on the packingline. Fungicide applications generally occur in the middle of sweetpotato packinglines. This allows the root surface to dry somewhat prior to packing into cartons. The high levels of decay found in the inoculated samples from the end of the packingline (packed carton) indicate that injuries are occurring post-application which are not protected by the fungicide. Botran is a very effective fungicide when applied to *R. stolonifer* inoculated wounds (Edmunds et al., 2006); however, the residual effect on wounds occurring after its application has not been tested.

Our results have important implications for the management of post-pack Rhizopus soft rot in sweetpotatoes. These results will be useful in the development of guidelines for modifying sweetpotato packinglines to reduce drop height and total impacts in order to reduce losses to Rhizopus soft rot, especially if susceptible cultivars are being handled. These results also suggest that packingline design might be modified to reduce the percent of roots which land on the more susceptible root end. These results also provide a quantitative assessment of the value of resistance in managing Rhizopus soft rot and indirect indications of the importance of sanitation. To further improve the management of Rhizopus soft rot, a predictive model which incorporates these results could be developed to optimize fungicide application to its gratest advantage.

Acknowledgements

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Table 3.1. Mean maximum impact force (m/s^2) associated with common impact surfaces on 23 sweetpotato packinglines in Louisiana and 17 packinglines in North Carolina.

Packingline component (impact surface)	Louisiana		North Carolina	
	number sampled[a]	mean impact (max impact)	number sampled[a]	mean impact (max impact)
dump tank (water/roots)[c]	20	141.3 (611.2) a[b]	14	90.3 (505.2) abc[b]
mechanical sizer (onto PVC bars)	23	132.4 (397.3) ab	10	146.2 (318.8) ab
mechanical sizer (onto plate-supported conveyor)	23	120.7 (450.3) abc	10	130.5 (357.1) abc
dump (metal bars)	4	120.7 (348.3)	2	154.0 (629.8) a
box fill (roots/fiberboard)	23	112.8 (530.7) abc	17	138.3 (711.2) abc
eliminator (metal rollers)	18	91.2 (539.6) abcd	17	89.3 (268.8) abc
grading table (PVC rollers)	29	87.3 (381.6) bcd	28	73.6 (286.5) bc
fungicide dip (water/roots)	11	75.5 (483.6) dc	7	60.8 (170.7) c
brushbed (plastic bristles)	34	69.7 (278.6) cd	32	71.6 (352.2) cb
conveyor (metal plate-supported plastic conveyor)	16	58.9 (254.1) d	30	100.1 (527.8) abc
metal (metal plate)	n/a	n/a	7	146.2 (369.8) ab
electronic sizer (metal)	n/a	n/a	2	115.8 (157.0) abc
sponge roll (2" sponge covered roller)	n/a	n/a	1	62.8(92.2) c

[a]Three to five replications per sample
[b]Means within a column followed by the same letter are not significantly different (p=0.05) according to the Student-Newman Keuls test.
[c]Shaded rows indicate packingline components that differ significantly (p=0.05) in impact force between states according to the Student-Newman Keuls test. Non-shaded rows do not differ significantly between states.

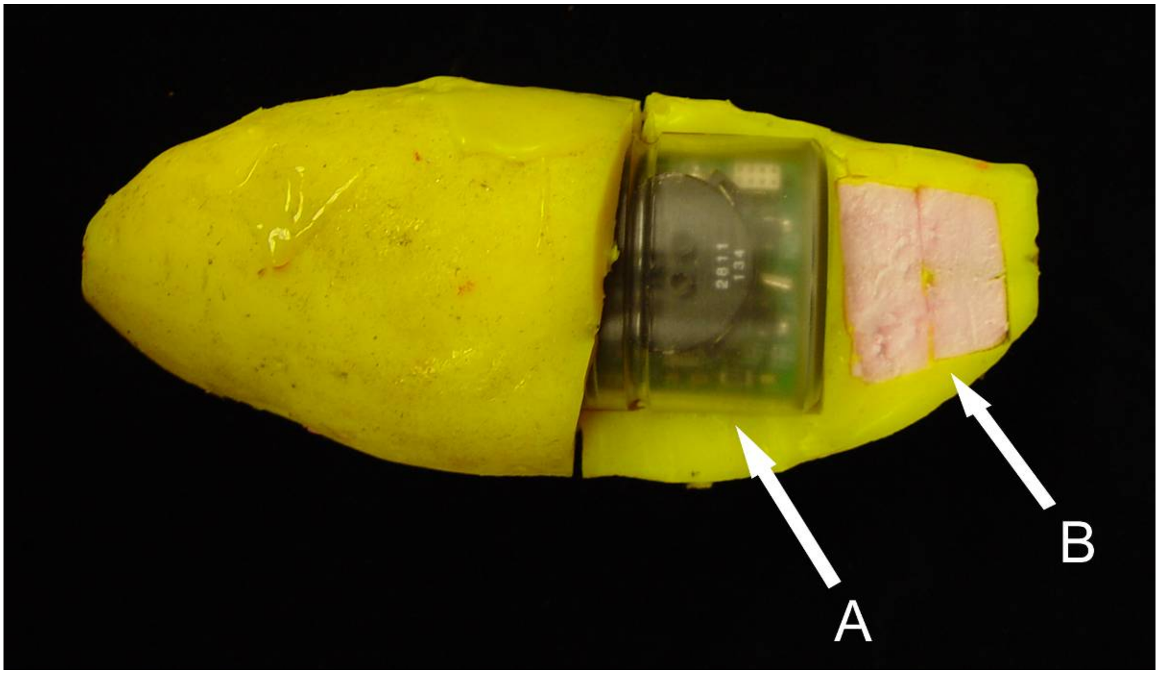

Figure 3.1. An impact recording device was used to quantify impact forces occurring on sweetpotato packinglines. A modified silicon casing that fits around the accelerometer (A) was fabricated using the dimensions of a U.S. No. 1 grade sweetpotato. The cutaway portion shows the foamcore filled pockets (B) added to increase buoyancy of the impact recording device.

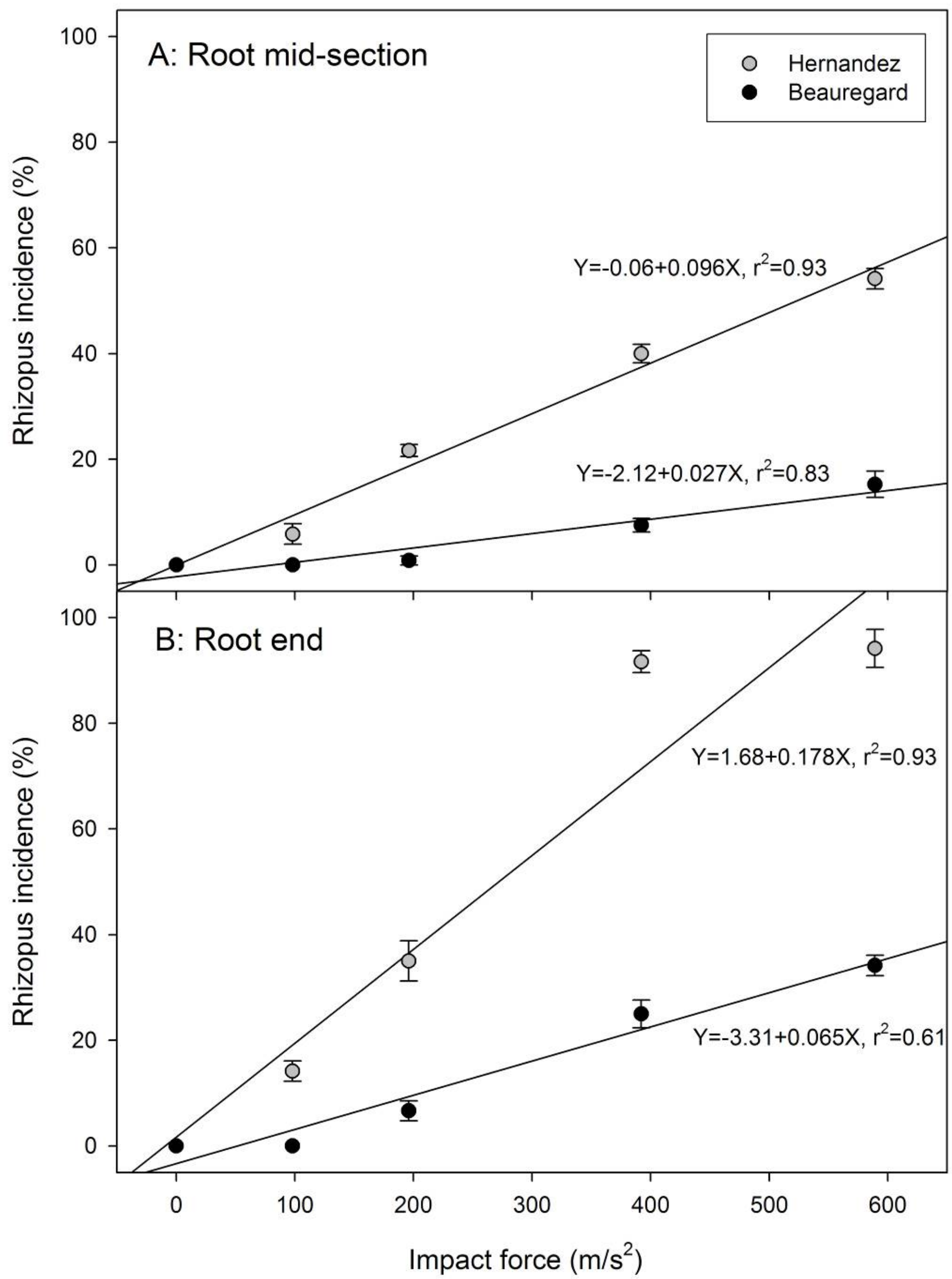

Figure 3.2. The effect of increasing impact forces on root midsections (A) and root ends (B) on the incidence of Rhizopus soft rot in inoculated Beauregard and Hernandez sweetpotatoes.

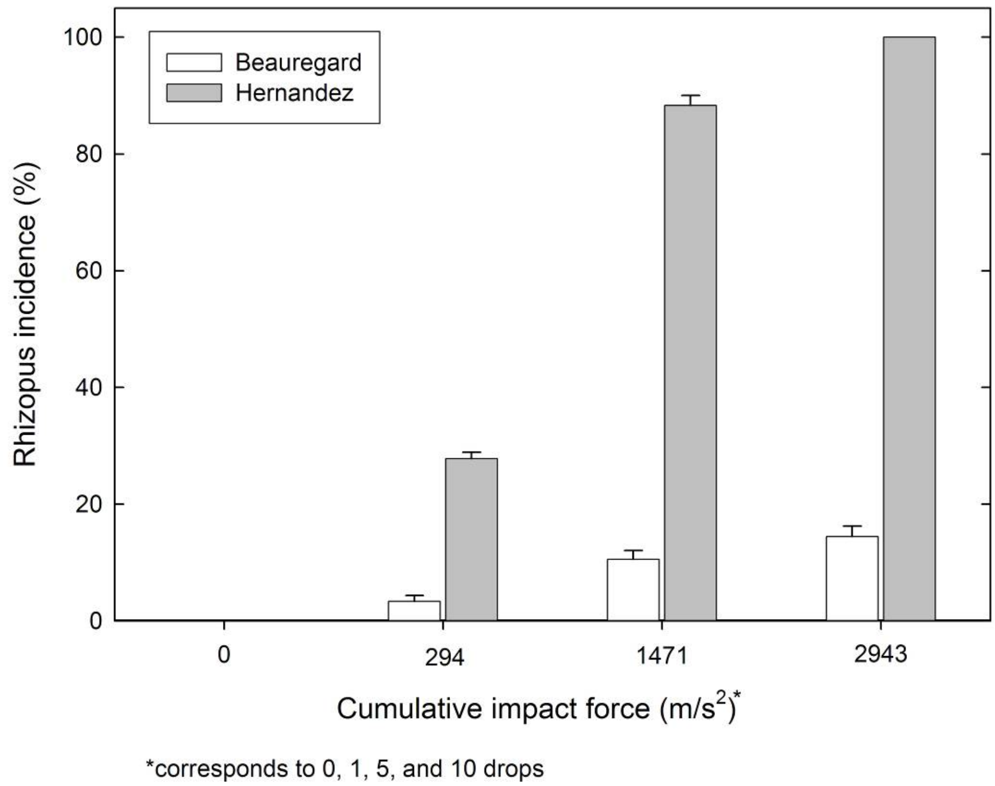

Figure 3.3. The cumulative effect passing sweetpotatoes repeatedly over a single packingline drop (height=30.5 cm/impact force= 294.3 m/s^2) on the incidence of Rhizopus soft rot in inoculated Beauregard and Hernandez sweetpotatoes.

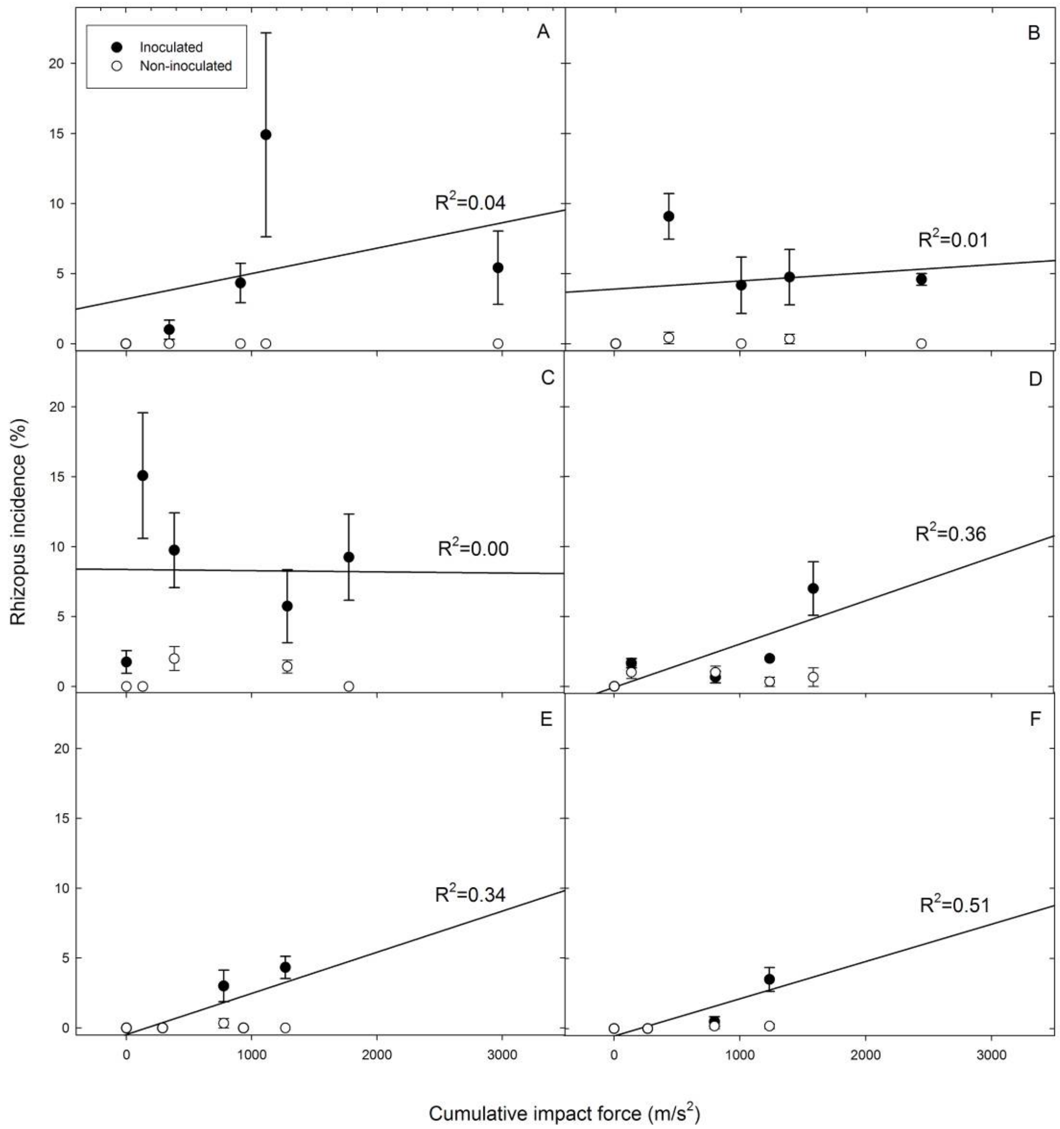

Figure 3.4. The effect of cumulative impact forces occurring on six commercial sweetpotato packinglines in NC (A-F) on the incidence of Rhizopus soft rot in inoculated and non-inoculated sweetpotatoes sampled at consecutive points on packinglines. The regression line indicates the relationship between decay incidence in inoculated roots and cumulative impact forces.

CHAPTER 4. EVALUATION OF ALTERNATIVE DECAY CONTROL PRODUCTS FOR CONTROL OF POSTHARVEST RHIZOPUS SOFT ROT OF SWEETPOTATOES

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Abstract

Postharvest Rhizopus soft rot of sweetpotato, caused by *Rhizopus stolonifer*, is managed by minimizing injuries incurred during harvesting and packing, curing roots immediately after harvest, and applying fungicide during packing. The U.S. sweetpotato industry relies heavily on a single fungicide (dicloran) to control Rhizopus soft rot, however, many markets (export, infant food, and organic) no longer allow dicloran residues. Dicloran is currently the only fungicide labeled for control of Rhizopus soft rot. Thirty-three products were tested in nine individual experiments over a 5 year period to identify alternative control products. The reduced-risk fungicides boscalid plus pyraclostrobin (Pristine) and fludioxonil (Scholar) significantly reduced Rhizopus soft rot and performed similarly to dicloran. The biological products, Bio-Save 10LP and 11LP, suppressed Rhizopus soft rot although results were variable among tests. Generally recognized as safe (GRAS) treatments were ineffective in controlling soft rot by our methods.

Introduction

Rhizopus soft rot, caused by the fungus *Rhizopus stolonifer*, is the most common postharvest disease of sweetpotatoes (*Ipomoea batatas* Lam.) (2). An estimated 2% of sweetpotatoes are lost to Rhizopus soft rot by the time they reach the retail market (3), but losses can be sporadic since only a few rotted roots can cause shipments to be rejected. *R. stolonifer* requires a wound for infection and to cause disease. Spores of *R. stolonifer* are ubiquitous in the environment, and in the presence of a wound, they germinate to produce mycelia and pectolytic enzymes which cause a soft, watery rot. Whiskery, white mycelium that becomes covered with powdery, black sporangiospores is a characteristic sign of *R. stolonifer* (Figures 4.1 and 4.2). An entire root can become completely rotted in 3 to 4 days after roots leave the packinghouse in good condition to arrive at their destination completely decayed.

Two key points where wounding can occur are during harvesting and packing. During harvest, roots are brought to the soil surface using specialized plows or chain diggers and hand-loaded into 20- or 40-bu capacity palletized bins. Wounds occur at the stem end where the root is removed from the plant in addition to wounds caused by digging equipment and the loading and transport of bins. Immediately following harvest, bins are transported to specialized storage rooms and roots are cured by exposure to high temperature (29°C) and relative humidity (85-90%). The curing process aids in healing harvest wounds and results in reduced losses during storage due to *R. stolonifer* and other diseases. After 5 to 7 days, the temperature is dropped to 13°C for long-term storage. In the U.S., sweetpotato roots are commonly stored for up to 12 months after harvest, enabling producers to provide a year round supply.

Roots are washed, graded, and shipped based on market demand. The packing process begins when pallet bins are brought out of storage and roots are poured into a large tank of water (dump tank) using either a forklift or mechanized system. The layout of individual packinglines varies, but all function to remove clinging field soil and sort the roots by grade (i.e. size, shape, and quality). A packingline has a series of overlapping components that remove soil through brushes and water sprays, applies fungicide, sorts roots by size and defects, and loads roots into fiberboard cartons. The cartons are usually stacked by hand onto pallets and loaded the same day into trailers for transport to market.

Sweetpotatoes can be wounded in three ways on packinglines: i) by ‘skinning’, when the skin or periderm is sloughed off the root; ii) by broken root ends that are snapped off by packingline workers or the packing process; and iii) by bruises when the root tissue is crushed during packing. Controlled experiments found that wounds caused by bruising result in increased susceptibility to infection by *R. stolonifer* as compared to the other types of wounds (9).

Management options for controlling Rhizopus soft rot of sweetpotato are limited. No cultivars are known to be completely resistant. Beauregard, the most commonly grown cultivar in the last 10 years, is considered moderately resistant to Rhizopus soft rot but susceptibility can vary greatly depending on preharvest conditions (4). This variability in susceptibility results in sporadic losses which tend to result in entire shipments being rejected at the point of sale.

To prevent losses from Rhizopus soft rot, the majority of sweetpotato packinghouses make prophylactic applications of the fungicide dicloran (Botran) as a spray or dip treatment on the packingline. Because the fungicide is applied so close to the time of consumption, the amount of residue left on the product is of great concern to regulatory agencies and consumers. As of January 2008, no residues of dicloran were allowed on exports to the European Union. Producers of infant food and organic foods also have a zero tolerance for dicloran residues. Because there are no other fungicides registered to control Rhizopus soft rot on sweetpotato, packers are forced to either lose these markets or risk losses incurred by shipping without fungicide protection.

The objective of this research was to identify alternative control products, including reduced-risk fungicides (newer fungicides considered to have a lower risk of human and environmental toxicity), biological products (formulations based on biological control organisms as the active ingredient), and GRAS compounds (products considered generally recognized as safe) for control of Rhizopus soft rot. The trial results for some individual years have previously been published (5, 6, 7, 8).

Product Efficacy Trials

A total of nine individual trials were conducted at either the Central Crops Research Station in Clayton, NC or the Horticulture Crops Research Station in Clinton, NC over a period of 4 years. U.S. No. 1 grade roots of cv. Hernandez were used in all trials as this cultivar is consistently susceptible to Rhizopus soft rot (1). All roots were grown commercially in North Carolina using standard cultural methods, cured after harvest, and stored at 13°C in a commercial storage facility until experiments were conducted. Roots were collected directly from bulk bins and transported to the research facility. One day prior to a trial, roots were gently handwashed with tap water and allowed to dry at room temperature.

The *R. stolonifer* isolate used in these trials was collected in 1992 from a sweetpotato root showing Rhizopus soft rot symptoms and signs and stored on silica crystals at 3ºC (12). To produce inoculum, silica crystals were transferred to potato dextrose agar (Difco; Sparks, MD) and held at room temperature (22°C) to induce production of sporangiospores. After 6 days, approximately 10 ml of sterile water was added to each plate and the sporangiospores were dislodged by gently rubbing the surface with a bent glass rod. The resulting suspension was filtered through four layers of cheesecloth to remove mycelial fragments and agar pieces. The spore suspension was diluted with 0.01% octylphenol ethoxylate (Triton™ X-15, Dow, New Jersey) to a concentration of 10^6 sporangiospores/ml to reduce clumping. The suspension was kept refrigerated (1-2°C) overnight.

Roots were inoculated using a technique developed for sweetpotatoes (9). First, an impact bruise (8 mm diameter × 1 mm deep) was made to opposite sides of the mid-section of each root by the calibrated impact of a wood dowel (Figure 4.3). Inoculum was introduced by brushing the *R. stolonifer* suspension over the wounded area with a 1-inch foam paintbrush (Figure 4.4).

After allowing the roots to airdry (ca. 60 minutes), fungicide treatments were applied. All treatments, except copper ionization treatment, were suspended in 10 gal of tap water. For the copper ionization treatment, the target concentrations of copper ions in solution were produced on-site using commercial ionizing equipment (Superior Aqua, Sarasota, FL) to treat 10 gallons of tap water. All treatments were applied by submerging roots in the treatment suspension for 30 sec unless otherwise noted. Roots were gently agitated while submerged to ensure complete coverage. A total of 33 treatments (17 products) were tested against the standard dicloran (Botran 75W, Gowan Company, Yuma, AZ) treatment in nine trials (Table 4.1). Three control treatments in each trial included: 1) non-wounded, non-inoculated; 2) wounded, non-inoculated; and 3) wounded, inoculated.

After treatment, roots were placed in commercial plastic storage crates (15/crate; four replicates/treatment). The crates were arranged in a randomized complete block design and stored at 16°C. Roots were evaluated for Rhizopus soft rot incidence after 10 days in storage (Figure 4.5). Infected roots were easily detected because 60-100% of the root mass was soft while non-infected roots were firm and showed no symptoms or signs of decay.

Disease incidence values for all trials and all treatments were combined and analyzed using ANOVA in SAS 8.0 (SAS Institute, Cary, NC) to compare treatments across trials. Data were standardized by weighting decay incidence in treatments against decay in the wounded, inoculated control to account for variability in susceptibility. No significant trial or treatment by trial interaction was seen. The Student-Newman-Kuel's test was used to separate means (P=0.05).

Wound colonization counts were completed on the first six trials of *Pseudomonas syringae* (Bio-Save 10LP and 11LP, Jet Harvest Solutions, Longwood, FL) treatments. Non-inoculated roots were puncture wounded (1 mm diameter x 4 mm depth) and the appropriate Bio-Save treatment was applied as previously described. The roots were allowed to air dry and shipped on ice packs to the Jet Harvest Solutions testing lab (Longwood, FL) for determining colonization. Roots arrived within 24 hours and *P. syringae* counts were completed by dilution plating onto nutrient yeast dextrose agar. Wound colonization counts were not done for the *Metschnikowia fructicola* (Shemer) treatments.

Effect of decay control treatments on Rhizopus soft rot

The inoculation method utilized in these trials resulted in high levels of disease (mean= 95.8%, std. dev.=7.3%) in the wounded, inoculated control across all experiments (Figures 4.6, 4.7, and 4.8). No decay developed in the non-wounded, non-inoculated control and very little decay developed in the wounded, non-inoculated control (mean=5.4%; std. dev.=9.1%). Dicloran (Botran) performed well in all trials (mean=10.4 %; std. dev.=9.9).

Fungicides. Boscalid plus pyraclostrobin (Pristine, 38WG, BASF Ag Products, Research Triangle Park, NC) was evaluated at four rates and in several different trials for a total of five treatments. These treatments resulted in low levels of decay that were not significantly different from dicloran (Figure 4.6). No significant rate effect was seen, although 36.3 fl oz/100 gal resulted in the numeric highest level of control (mean=10.9%; std. dev.=4.2).

Fludioxonil (Scholar 50WP, Syngenta Crop Protection, Greensboro, NC) performed similar to dicloran in tests of two formulations, a wettable powder (50WP) and a soluble concentrate (250SC) No significant differences were found in efficacy of the two formulations or rates (Figure 4.6). The treatment duration (30 vs. 60 second dip) had no significant effect on performance of fludioxonil (Scholar 50WP 16 oz (11.4% and 7.4%, respectively). Maxim 4FS (Syngenta Crop Protection, Greensboro, NC), which is a seed treatment formulation for use only on sweet potato at planting, was tested in early trials and significantly reduced Rhizopus decay (mean=17.9 %, std. dev.=0.6 %). Maxim 4FS is labeled for control of Rhizopus rot during transplant production but not postharvest use.

Fenhexamide (Elevate 50WDG, Arysta LifeScience North America, Cary, NC) was not effective in control of Rhizopus soft rot in this study. These results were not surprising as fenhexamide has also proven ineffective in the control of Rhizopus soft rot in other commodities such as strawberry and against *R. stolonifer* in vitro (13).

Sodium o-phenylphenol (SOPP; Freshgard 25, FMC Corporation, Philadelphia, PA) was moderately effective against Rhizopus soft rot. SOPP registrations were dropped in 2005 because it irritates skin and mucous membranes (i.e., eyes and throat) and was considered more hazardous to workers than dicloran.

Bio-fungicides. None of the biological treatments performed as well as dicloran, but some suppression of Rhizopus rot were indicated by three products (Figure 4.7).

Bio-Save 10LP and 11LP are two different strains of non-pathogenic *Pseudomonas syringae* (strain ESC10 and ESC11, respectively). The Bio-Save 10LP is labeled for control of Mucor rot of apples, caused by *Mucor piriformis* which is closely related to *R. stolonifer*.

Averaged over all trials, treatments with *P. syringae* (except 22 oz of Bio-Save 11LP) were not effective in control of Rhizopus soft rot. A rate effect was seen in tests of Bio-Save 10LP but was not apparent in tests of the 11LP (Figure 4.7). There was no significant difference in efficacy at the high rate (70.5 oz rate) of each formulation, although the mean decay was lower in the LP10 compared to LP11 (41.2 % vs. 54.5 % decay). Based on an early trial showing high efficacy, Bio-Save 11LP was labeled for use on sweetpotatoes in 2005 (5, 6). Subsequent testing has demonstrated high variability across trial dates. Wound colonization by *P. syringae* in the first six trials fell within the expected range for the treatment rate and was not significantly different among trial dates (data not shown), making it unlikely to be responsible for reduced efficacy.

The tank-mix of boscalid plus pyraclostrobin with BioSave LP11 improved control compared to either product alone. The cause of increased efficacy is unknown, although the different modes of action may have resulted in an additive effect.

Shemer (AgroGreen Minrav) is the trade name for a bio-fungicide developed in Israel; the active ingredient is a strain of *Metschnikowia fructicola*,. Preharvest applications of *M. fructicola* have significantly reduced postharvest decay of strawberries which is caused by a mixed infection of *R. stolonifer* and *Botrytis cinerea* (10). None of the treatments with *M. fructicola*, with or without 0.01% potassium bicarbonate, reduced decay significantly.

Generally recognized as safe (GRAS) Treatments. Rhizopus soft rot was not prevented by any GRAS product tested as decay in all was similar to the inoculated control (Figure 4.8). This was not surprising as most products tested are labeled as sanitizers, not fungicides. As in other commodities, many products are marketed to sweetpotato packers with claims of disease control efficacy but have limited supporting data. GRAS products were included in these trials to provide replicated trial data for judging efficacy.

Calcium chloride has been used as a successful postharvest treatment of peaches for control of brown rot caused by *Monilinia laxa* (15), but was ineffective against *R. stolonifer* in this trial. Potassium bicarbonate used alone did not significantly reduce decay. Potassium sorbate, a prepared-food preservative, also failed to reduce decay in these trials. Rhizopus soft rot of apricots was less for fruit treated by potassium sorbate, but not for fruit of nectarines or sweet cherries (11). Heating the treatment suspension and/or adjusting the pH may increase efficacy of potassium sorbate (14).

Tsunami 100 (Ecolab, St. Paul, MN), StorOx (Bio-safe Systems, LLC, East Hartford, CT), and sodium hypochlorite are used to sanitize packinglines and commonly added to dump tanks on sweetpotato packinglines. While these products may reduce microbial counts in water, none were effective in controlling Rhizopus soft rot in these trials.

Copper ionization has been proposed as a sanitizing method for agricultural water and some companies are marketing the technique for disease control. Roots treated in copper ionized water for 30 or 120 sec developed as much Rhizopus soft rot as the wounded, inoculated control.

Summary

These trials have identified two reduced-risk fungicides, Scholar and Pristine, with the ability to effectively control Rhizopus soft rot of sweetpotatoes. The active ingredient in Scholar, fludioxonil, is known to be effective against Rhizopus soft rot of peaches and is labeled for postharvest use on that crop (16). Boscalid plus pyraclostrobin (Pristine) is effective at reducing Rhizopus soft rot of strawberries (13). Scholar and Pristine are not labeled for use on sweetpotatoes, however, a label for Scholar is expected in November 2008 (A. Talley, Syngenta Crop Protection, Personal communication).

The biological control products were not as effective as the reduced-risk fungicides in these trials. Bio-Save 11LP showed suppression of Rhizopus soft rot and is currently labeled for postharvest applications on sweetpotatoes. Additional work is needed to optimize and stabilize efficacy of Bio-Save 11LP. These results also confirm that products labeled as sanitizers (i.e., bleach, acetic acid, copper ionized water, etc) are ineffective against Rhizopus soft rot by the methods used in this study.

Trial products were only tested using a single application method: dipping in a treatment suspension for 30 or 120 sec. Many packing houses use overhead sprays over rotating brushes or a tank mix fungicide combined with food grade waxes to improve root appearance. Preliminary tests with dicloran show no significant difference between dip and overhead spray above rotating brushes (data not shown). Additional research is needed to understand the interaction of fungicides with waxes and the efficacy of other application methods. Furthermore, performance may be influenced by the method of inoculation. Disease incidence in the wounded, inoculated control is far greater than would be expected under normal commercial practices. However, dicloran, fludioxonil, and boscalid plus pyraclostrobin were highly effective under the conditions of our experiments.

Acknowledgments

This research was supported, in part, by the USDA-CSREES Risk Avoidance and Mitigation Program (Project No. NC09197), the North Carolina Sweetpotato Commission and The IR-4 Project-Biopesticide Program. The authors thank Mike Adams for providing technical support.

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Table 4.1. Products tested for efficacy against Rhizopus soft rot of sweetpotatoes, 2003-2008.

Treatment [Active ingredient(s)]	**Product rates trials (per 100 gal)***	**Trade name; Company**
dicloran	1 lb	Botran 75W; Gowan Company LLC
boscalid + pyraclostrobin	9.1, 18.1, 36.3, 72.5 oz	Pristine 38WG; BASF Ag Products
fludioxonil	16.5, 33 fl oz	Scholar 230SC; Syngenta Crop Protection
fludioxonil	8, 16 oz	Scholar 50WP; Syngenta Crop Protection
fludioxonil	1.6 fl oz	Maxim 4FS; Syngenta Crop Protection
fenhexamid	24 oz	Elevate 50WDG; Arysta LifeScience
SOPP (sodium o-phenylphenol)	89.3 fl oz	Freshgard 25; FMC Corporation
Pseudomonas syringae strain ESC10	22, 70, 70.5 oz	Bio-Save 10LP; Jet Harvest Solutions
P. syringae strain ESC11	22, 70.5 oz	Bio-Save 11LP; Jet Harvest Solutions
boscalid + pyraclostrobin tank mixed with *P. syringae* strain	18.1 oz + 22 oz	Pristine 38WG; BASF Bio-Save 10LP; Jet Harvest Solutions

ESC10		
Metschnikowia fructicola	13.4 oz, 26.7 oz	Shemer, AgroGreen Minrav
M. fructicola tank mixed with $KHCO_3$	13.4 oz + 0.01%; 26.7 oz + 0.01%	Shemer; AgroGreen Minrav $KHCO_3$; Fisher Scientific
sodium hypochlorite	50 ppm, 200 ppm	Clorox; The Clorox Co
calcium chloride ($CaCl_2$)	8.35 lb	Fisher Scientific
copper ionized water	5.2 ppm	Superior Aqua
potassium sorbate ($C_6H_7KO_2$)	3, 5 %	Fisher Scientific
hydrogen dioxide	15, 125 fl oz	StorOx; BioSafe Systems, LLC
acetic acid+peroxyacetic acid +hydrogen peroxide	6 fl oz	Tsunami 100; Ecolab
potassium bicarbonate ($KHCO_3$)	0.01%	Fisher Scientific

*Rate is expressed as amount of formulated product per 100 gallons of water

Figure 4.1. *Rhizopus stolonifer* sporulation on sweetpotato root.

Figure 4.2. Rhizopus soft rot in packed container.

Figure 4.3. Close-up of inoculation wound (8 mm diameter × 1 mm deep) utilized in these studies.

Figure 4.4. Applying *R. stolonifer* suspension to wounded areas on roots. Arrow indicates wound.

Figure 4.5. Diseased roots at 10 days after inoculation. Softening and sporulation are evident around the inoculated wound.

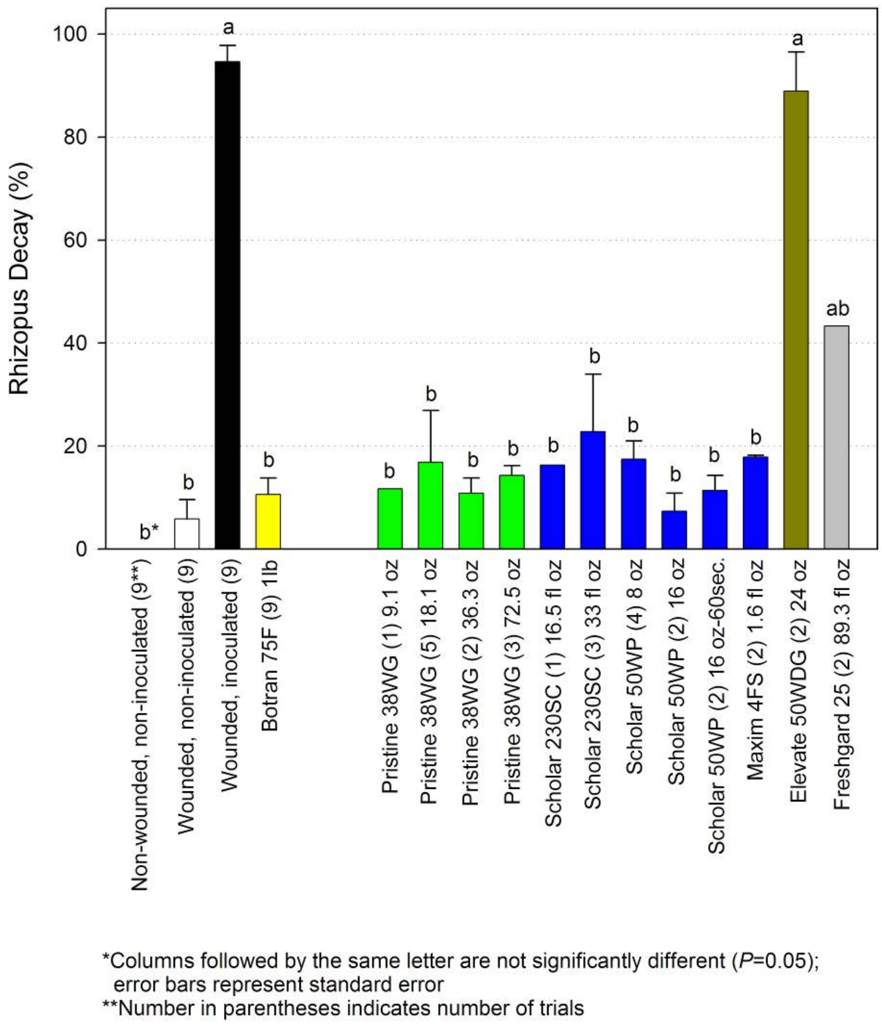


Figure 4.6. Efficacy of alternative fungicides against Rhizopus soft rot of sweetpotatoes, 2003-2008.

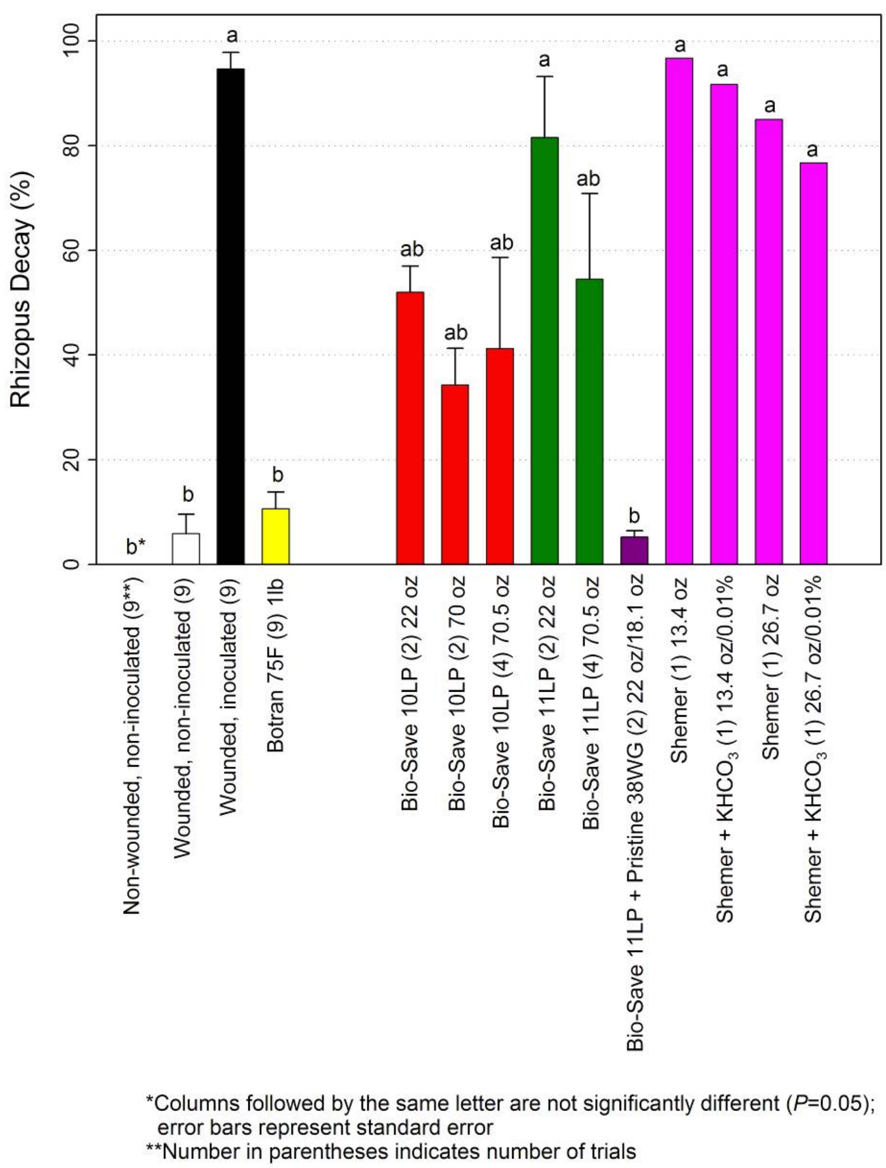
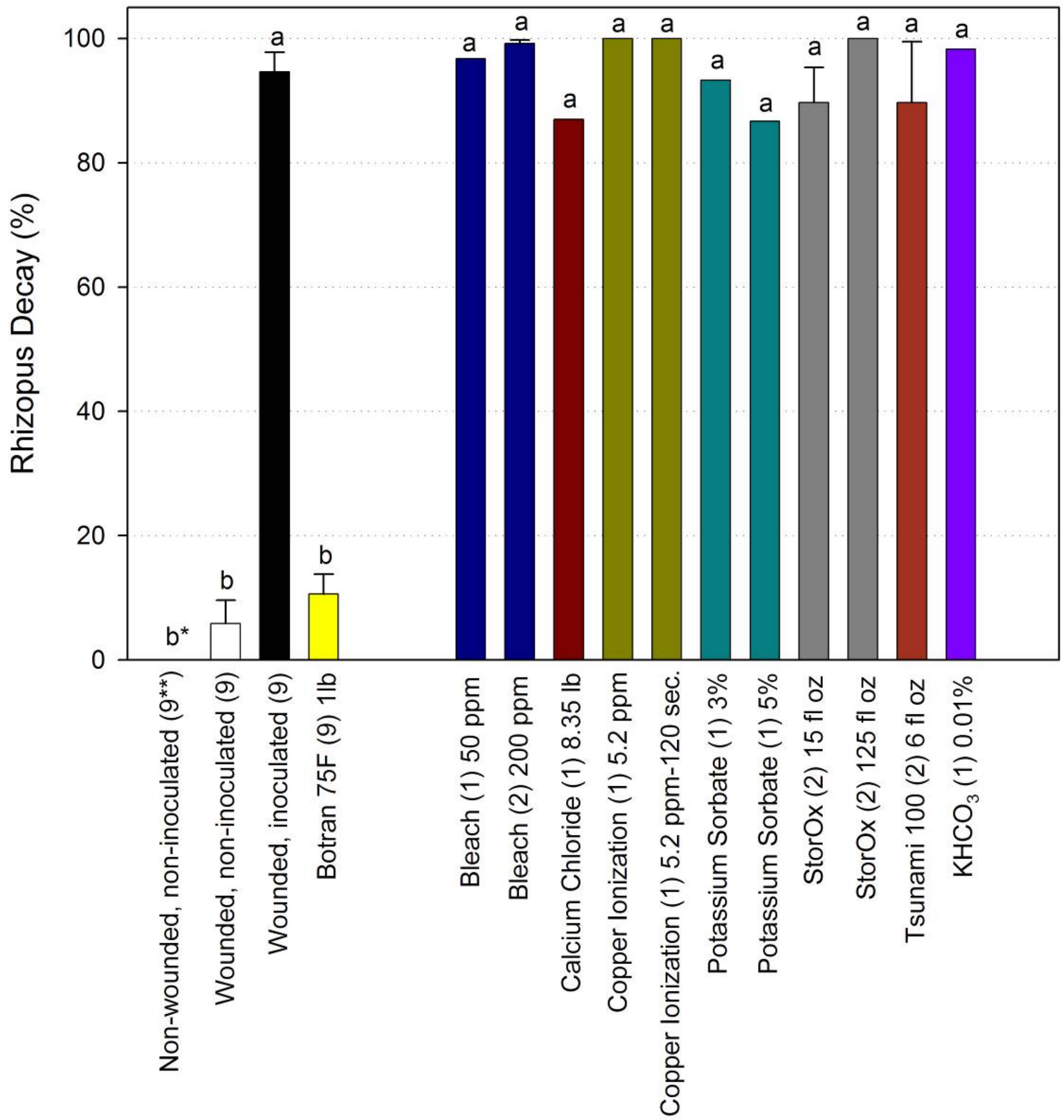


Figure 4.7. Efficacy of bio-fungicides against Rhizopus soft rot of sweetpotatoes, 2003-2008.

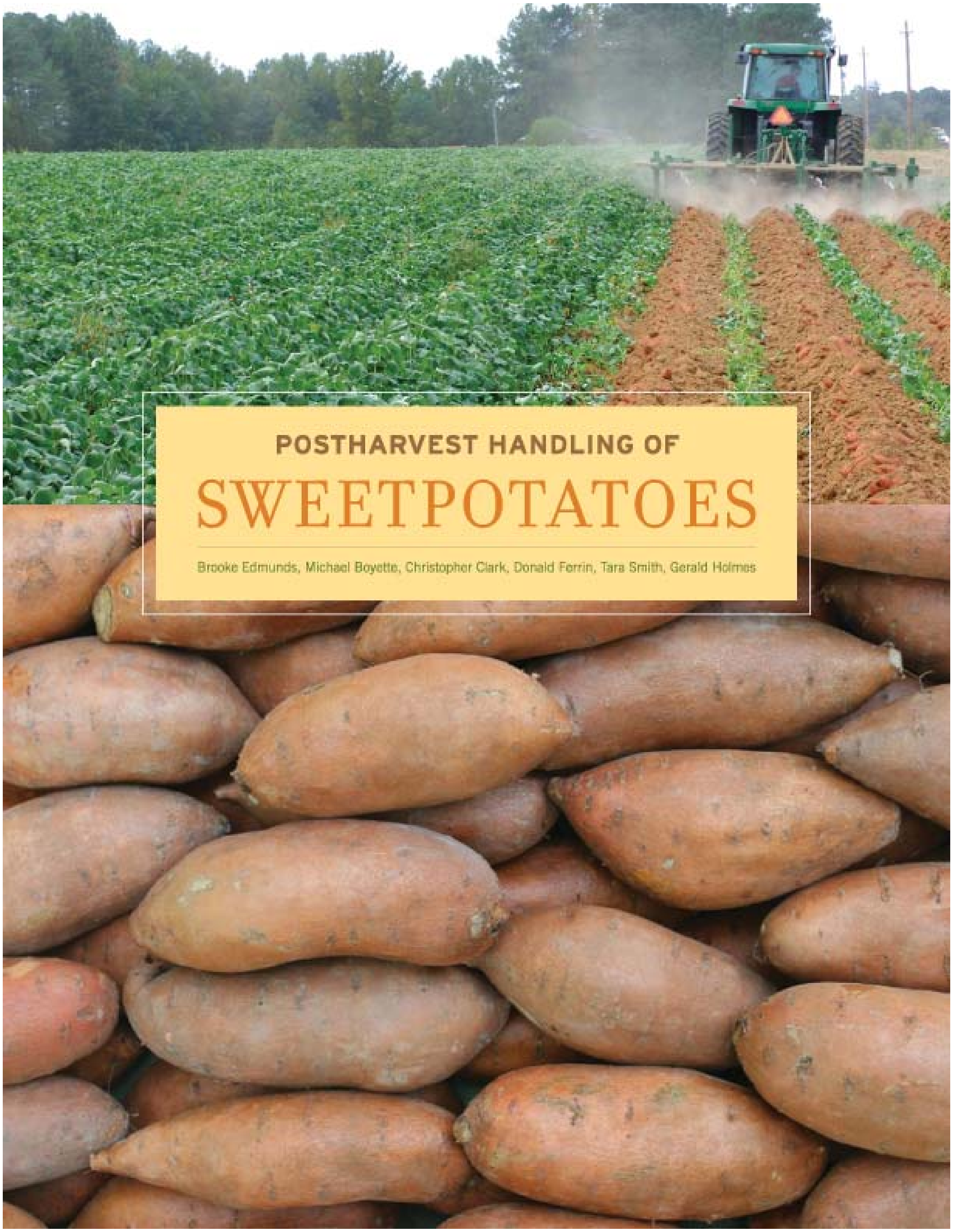


*Columns followed by the same letter are not significantly different (*P*=0.05); error bars represent standard error
**Number in parentheses indicates number of trials

Figure 4.8. Efficacy of generally recognized as safe (GRAS) products against Rhizopus soft rot of sweetpotato, 2003-2008.

CHAPTER 5. MULTI-STATE EXTENSION BULLETIN: POSTHARVEST HANDLING OF SWEETPOTATOES.

The following document is an Extension bulletin published in August 2008 and first authored by Brooke A. Edmunds. This publication was a complete revision of a 1997 Extension bulletin of the same title. Information was updated based on the most recent research on how packingline impacts affect disease development and new sections were added on food safety and packingline sanitation.


POSTHARVEST HANDLING OF
SWEETPOTATOES
Brooke Edmunds, Michael Boyette, Christopher Clark, Donald Ferrin, Tara Smith, Gerald Holmes


NORTH CAROLINA
SWEET POTATO
50 lbs. net
PACKERS
LOUISIANA YAMS
Sweetpotatoes/Yams
POINTER BRAND
A Pointer on Quality
GODWIN PRODUCE CO.
OUR SPECIALTY IS HOUSE CURED YAMS
The Pride of North Carolina
DUNN, NORTH CAROLINA
North Carolina
SWEET POTATOE
Sweet Potatoes
YAMS
WASHED
WAXED
CAJAN QUEEN
SWEET POTATOES
TEXAS
Sweet Potatoes
SWEET MAGNOLIA
SWEET POTATOES
SAMPSON KING
NUTRITIONALLY FRESH
SWEET POTATOES/YAMS
Distributed by Wayne E. Bailey Produce Co.
PURE WINNER
SWEET POTATOES
Dri-Pak
NORTH CAROLINA
SWEET
YAMS
SHARKEY'S FINEST
Cajan
GOLD
Yams
NORTH CAROLINA
Queen Ann
WASHED AND WAXED
YAMS
SWEET POTATOES
40 LBS. NET
NORTH CAROLINA
YAMS
MORNING GLORY
LOUISIANA
PORTO RICAN
SWEET
POTATOES
U.S. No. 1
WAYNE E. BAILEY
NUTRITIONAL ALL STARS
Cajun
SWEET POTATOES
YAMS
CAJUN GOLDEN
LOUISIANA BEAUREGARD YAMS
NORTH
CAROLINA
SWEET POTATOES
NATURALLY
BAYOU MAID
LOUISIANA
PORTO RICAN
SWEET
POTATOES
U.S. No. 1
TATER GATOR
BEAUREGARD
YAMS
NASH'S
NORTH CAROLINA
YAMS
SWEET POTATOES
NUTRITIONALLY
Play Boy
SWEET POTATOES/YAMS
40 LBS. NET
NET WT.
JUMBO
SWEET
POTATOES
DEER MARK
SWEET
POTATOES
DOVE
Louisiana
YAMS
OYELLES
SWEET POTATOES

POSTHARVEST HANDLING OF

SWEETPOTATOES

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ON THE COVER: (Top) The process of harvesting sweetpotatoes involves digging the roots. Here the soil is turned over using large disks that bring sweetpotato roots to the surface. (Bottom) High quality, fresh-market sweetpotatoes (cultivar Covington) cured, washed and ready for sale.

SWEETPOTATO AS ONE WORD: Throughout this book, sweetpotato is deliberately spelled as one word unless directly quoting a source where it is spelled as two words (i.e., sweet potato). The one-word spelling was officially adopted by the National Sweetpotato Collaborators in 1989. Sweetpotato (*Ipomoea batatas*) must not be confused in the minds of shippers, distributors, warehouse workers, and above all consumers with the equally unique and distinctive potato (*Solanum tuberosum*) or the yam (*Dioscorea* sp.) which are also grown and marketed commercially in the United States.

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Proper Handling Pays

The importance of proper handling of sweetpotatoes, from the farmer's field to the consumer's kitchen, cannot be overemphasized. Studies show that significant postharvest losses occur because of improper handling and other factors. On average in the United States, 20 to 25 percent is lost in sweetpotatoes during curing and storage, another 5 to 15 percent is lost during shipping and retailing, and an additional 10 to 15 percent is lost after sweetpotatoes reach the consumer. In total, poor handling practices may result in the loss of more than half the harvested sweetpotatoes before they reach the consumer's table.

Providing consumers with an acceptable product (Figure 1) demands attention to the unique postharvest requirements of sweetpotatoes. This publication has been prepared to acquaint growers, packers, and shippers with the most current information and recommendations for proper postharvest handling of sweetpotatoes. It incorporates new information on good agricultural practices (GAPs) and packing line sanitation and configurations, and the results of an in-depth packing line survey. Also included are plans and operating recommendations for a moderate-sized sweetpotato curing and storage facility with negative horizontal ventilation (NHV). Photographs of common postharvest diseases, abiotic damage not caused by disease organisms, and insects are in Appendix 1.

Figure 1. Proper postharvest handling is required to produce quality sweetpotatoes for retail markets. (PHOTO BY G. HOLMES)

Figure 2. Freshly harvested roots exude latex when cut. (PHOTO BY G. HOLMES)

Figure 3. No latex exudation when cut: a symptom of chilling injury. (PHOTO BY T. SMITH)

Figure 4. Proper cutting of slips is done above the soil line to avoid contact of the knife blade with soil. A contaminated blade may transfer disease organisms from the soil to the cut ends of slips. (PHOTO BY G. HOLMES)

Growing for Improved Postharvest Quality

Successful storage starts with high-quality roots. Events occurring during the growing season may later negatively affect postharvest quality. Some factors such as weather are impossible to control, whereas others (such as fertilization) can be manipulated by a grower to ensure that a quality product goes into storage.

The weather during the growing season, especially just before and during harvest, has a major effect on postharvest quality. An extended drought followed by heavy rain frequently accelerates growth, which often produces roots with thin, delicate skin that are prone to growth cracks (Figure 53). Besides being unappealing to the customer, these cracks provide infection sites for soilborne pathogens. Additionally, heavy rains that saturate soil for more than a few hours can cause root asphyxiation. Water-saturated soil allows carbon dioxide to accumulate in the roots, a condition that may also be accompanied by a depletion of oxygen. Asphyxiation can happen at any time, but it is more likely to occur during warm periods, especially if the vines have been removed before harvest. Sweetpotatoes that have been asphyxiated may appear healthy for several days or weeks, but if injury was severe, the roots will die and begin decomposing in storage. The first indication of a problem may include the lack of exuding latex from the vascular ring of a cut sweetpotato (Figures 2 and 3). The smell of alcohol, yeast or "decay," increased numbers of fruit flies, and secondary diseases such as bacterial or fungal infections also appear during storage of asphyxiated sweetpotatoes.

Nitrogen fertilization timing and rates affect postharvest quality. While the final studies are not in yet, good cultural practices dictate the use of nitrogen fertilizers early and sparingly. Increasing yield with additional nitrogen fertilizer may result in an abundance of large, misshaped roots. Research on calcium fertilizers has also produced variable results. Some studies show a beneficial effect on skin quality and appearance, while most show no effect on quality.

Field practices control some postharvest diseases. Fusarium root rot, Fusarium surface rot, and black rot are just three diseases that start as infections in the field but develop symptoms in storage. Growers can reduce losses from these diseases by avoiding fields with a known history of disease and by using slips (plant cuttings used as transplants) that have been cut instead of pulled, which avoids transferring disease from the plant bed into the field (Figure 4). Proper curing is also essential to controlling many diseases and is discussed in the curing section on page 11.

Harvesting for Quality

Sweetpotatoes have thin, delicate skin that is easily damaged by cuts and abrasions (Figure 5). Rough handling during harvest can contribute significantly to postharvest losses. These losses result from shrinkage (weight loss), inferior appearance of the roots, and diseases that enter through damaged skin. Plowing and hand harvesting or harvesting with a mechanical digger will give satisfactory results if done carefully. Most growers harvest into either 20-bushel or 40-bushel "double" wooden bins, although some 20-bushel plastic bins are used. (See page 44 for more details on pallet bin dimensions and capacity.) Workers should not throw or step on the roots in the bins (Figure 6). Pallet bins should never be overfilled, as this prevents proper bin stacking. Improper stacking will injure the roots, not just on top, but throughout the bin (Figure 7). Overfilling can also

Figure 5. Skinning due to abrasions incurred during postharvest handling. (PHOTO BY G. HOLMES)

Figure 6. Gentle handling during harvesting operations is critical to maintaining quality and reducing decay. (PHOTO BY G. HOLMES)

Figure 7. Bins are often slightly overfilled initially so that as roots settle, the bin's holding capacity remains maximized. However, if sufficient settling does not occur, overfilled bins will lead to tremendous injury when stacked. (PHOTO BY G. HOLMES)

Figure 8. Sunscald (A) with deer feeding injury (B); undamaged root skin under the soil line (C). (PHOTO BY G. HOLMES)

Figure 9. Surface pitting caused by chilling injury. (PHOTO BY G. HOLMES)

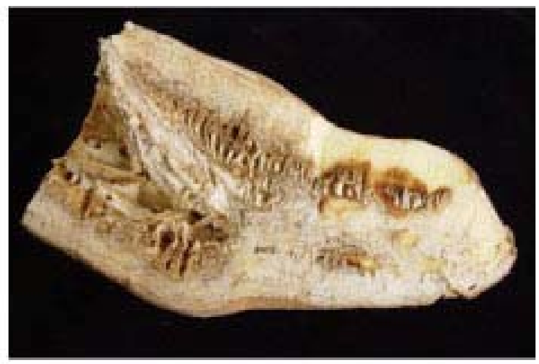

Figure 10. Internal voids caused by dry matter loss. (PHOTO BY G. HOLMES)

Figure 11. Secondary *Penicillium* mold invasion following chilling injury. (PHOTO BY G. HOLMES)

cause stability problems when stacking. Likewise, transport over rough roads or excess movement at the curing and storage facility can result in additional damage. Although prompt and proper curing can help heal injuries, an injured sweetpotato will never regain its original appearance.

After roots are dug, they should be promptly loaded and moved to the storage facility. Otherwise, there is a risk of injury by sunscald or chilling, depending on environmental conditions. Sunscald (Figure 8), a physiological condition that causes a darkening or death of the skin, may result after as few as 30 minutes of exposure to bright sunlight. If sweetpotatoes are allowed to remain in bright sun for several hours, either before they are picked up or after they are placed in the pallet bin, they are almost sure to develop sunscald. Sunscald is unattractive and can be a site for postharvest decay. Some cultivars of sweetpotatoes are more susceptible to sunscald than others, and it is more conspicuous on light or flesh-colored cultivars.

Chilling injury becomes a concern during late-season harvests. Although sweetpotatoes freeze at about 30°F (1°C) and are immediately ruined, they are injured at temperatures below 50°F (10°C). The extent of the chilling injury is a function of both the temperature and length of exposure. For example, one hour at 40°F (4°C) may produce the same level of injury as five hours at 45°F (7°C). Chilling injury is also cumulative; one short episode below 50°F (10°C) may not produce any noticeable injury, whereas many short episodes may cause significant injury. Unharvested sweetpotatoes may not be harmed by a frost, depending on the temperature of the soil surrounding the roots. Harvest as soon as possible after frost has killed the vines to ensure that no injury occurs. Never leave harvested sweetpotatoes in the field overnight, as cooling may cause substantial injury. Damage caused by chilling may not appear for many weeks—or even several months—after the chilling occurs.

Chilling injury is expressed in many ways and can be difficult to diagnose. The most common symptoms are surface pitting, greatly accelerated respiratory activity (dry matter loss), and an increase in susceptibility to decay (especially blue mold caused by *Penicillium* spp. See Figures 9 through 11). Other common symptoms include internal breakdown and voids, hardcore, failure to sprout, reduced culinary character (color, texture, taste, and aroma), and discoloration (darkening) of flesh when exposed to air. If chilling was severe, the roots may not exude latex when cut (Figures 2 and 3), or die and begin to decompose in storage.

The Curing and Storage Facility

A properly built storage facility maintains the temperature and humidity required for curing and long-term storage of sweetpotatoes. "Common storage" in areas without temperature control or assuming that the ambient cool winter temperatures are adequate will not maintain sweetpotato quality. The most effective type of storage facility uses negative horizontal ventilation (NHV).

The NHV system uses a slight negative pressure to pull the ventilation air horizontally past the pallet bins. Fans mounted internally along the top of a plenum wall on one end of the room create the negative pressure. Air first enters the mass of sweetpotatoes at the end of the room opposite the plenum wall, through ducts formed by the forklift slots at the bottom of the pallet bins. The air then moves horizontally through the mass of sweetpotatoes toward openings in the plenum wall. Once in the plenum, the air rises and passes through the fans and back out into the room, where it moves horizontally in the opposite direction back over the top of the stacked bins (Figures 12 and 13).

Figure 13. Loading pallet bins of sweetpotatoes into a new negative horizontal ventilation (NHV) facility.

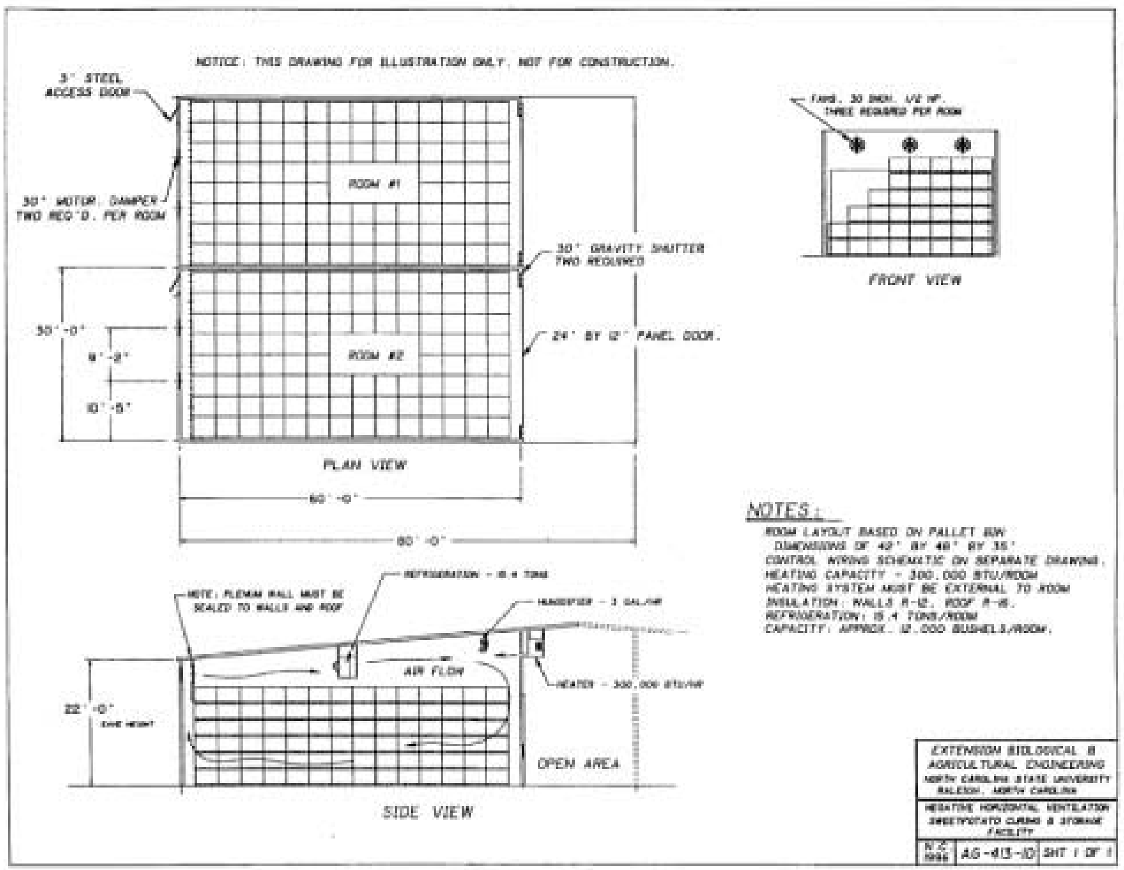

Figure 12. Construction diagram for negative horizontal ventilation storage facility.

The NHV system allows good air mixing, so there is little internal variation in temperature or humidity throughout the room. Further, because the air is in motion and is passing through the mass of sweetpotatoes (no root is more than one-half the depth of a pallet bin—approximately 25 inches (63.5 cm)—from a moving stream of air), there is opportunity for heat transfer. Good heat transfer is important for warming the sweetpotatoes at the beginning of the curing cycle, cooling them at the end, and for removing the heat of respiration throughout the storage period.

A series of motorized dampers is located on the exterior wall across the plenum from the fans. While these dampers remain closed, only internal air is circulated through the pallet bins. These dampers are opened when outside air is required for ventilation or cooling. Air is pulled into these openings because of the slight negative pressure the fans create in the plenum. The size and number of these dampers are determined by the capacity of the room. When correctly designed, approximately one-third of the air passing through the fans will be pulled from outside, with the remainder of the air recirculated from the stack of pallet bins. The air displaced by the incoming air exits the room through gravity shutters located near floor level at the end of the room opposite the plenum.

The NHV system offers a number of improvements to sweetpotato curing and storage facilities:

- Air moves efficiently and consistently through the large mass of sweetpotatoes, providing ventilation and heat transfer to minimize both in-building variations and fluctuations because of changes in outside temperature and humidity. Warming sweetpotatoes at the beginning of curing, cooling at the end, removing heat, and warming seed sweetpotatoes for pre-sprouting before bedding are greatly enhanced by NHV's efficient heat transfer.
- Because the air passes through the mass of sweetpotatoes horizontally, the NHV system does not use floor trenches. The floors may be the standard four inches of welded wire mesh or fiberglass-reinforced concrete over a packed grade. This feature substantially reduces the cost of construction and allows NHV systems to be installed in many existing structures.
- Economical standard pole-type or steel column and girder buildings may be used without expensive custom modifications or the need for excessively wide spans.
- The system can accommodate a large variety of room sizes. Individual rooms have been built as small as 20 by 50 feet (6.1 by 15.2 m), with 6,000-bushel capacity, to as large as 120 by 100 feet (36.6 by 30.5 m) with 96,000-bushel capacity. This flexibility is particularly attractive in the larger facilities with lower per-unit construction and operating costs. Larger rooms may make slightly more efficient use of space than smaller rooms but can result in undercured or overcured roots if not filled on a timely basis. Smaller rooms, however, are more quickly emptied and taken out of service.
- The NHV system makes very efficient use of floor space. For the system to operate properly, the pallet bins must be placed tightly together, in straight rows, with as little space between bins as possible. The system has worked well with bins stacked six, seven, and even eight high, but it works best if all the bins are stacked to the same height. It is also better if all the pallet bins are nearly the same size and of the same construction, as this facilitates proper stacking and minimizes air leakage between bins. Some air will inevitably short circuit between the bins, both in the horizontal and vertical direction, which is why the fans are sized to accommodate this leakage.
- Because the cost of outfitting a building with NHV is modest, there is no advantage to having separate rooms for curing and storage. This makes better use of space and eliminates the need to move the sweetpotatoes at the end of curing—an operation that is time consuming, expensive, and invariably results in damage to the roots.
- Eliminating substantial variations in temperature and humidity inside the room allows for more precise and sophisticated controls that help maintain quality and reduce energy usage. Although many NHV facilities are successfully managed by electro-mechanical controllers (thermostats, relays, timers), the full benefit of NHV technology is realized by using programmable logic controllers (PLCs). These industrial, computer-like devices may be programmed not only to control the temperature and humidity but also to monitor and limit energy use, collect data, sound alarms, and provide security.
- The ventilation fans mounted in the roof of traditional sweetpotato storage facilities are often a source of leaks and other maintenance problems. In an NHV facility, air inlets and outlets are mounted on the sides of the building, which makes them much easier to install and maintain and less likely to leak.
- Various sprays are effective against insect pests. Until recently, however, it was difficult to consistently distribute the material throughout the mass of sweetpotatoes. Even in facilities with automatic insecticide dispersal systems, complete coverage is difficult. The uniform air movement in NHV facilities effectively distributes insecticides throughout the room for maximum coverage.

For more information on specific construction guidelines for the NHV system, see Appendix 3.

Curing for Quality

A portion of the annual sweetpotato crop is still marketed as "green," although the practice is fading from favor. Green roots are washed, graded, and packed within a few hours or days of harvest and shipped immediately to buyers without curing. Uncured sweetpotatoes generally lack the visual appeal, shelf life, and culinary character of cured roots.

Most sweetpotato growers and packers have invested in modern curing facilities and consider proper curing an indispensable first step in a process that allows the industry to provide a year-round supply of high-quality sweetpotatoes. Successful curing requires roots to be held at a temperature of 85°F (29°C) and a relative humidity of 85 to 90 percent with proper ventilation for three to five days immediately after harvest. (The duration varies depending on the root pulp temperature at harvest. The greater the difference between root pulp temperature and 85°F (29°C), the longer it will take to cure. See page 47 for more information.) A delay of as few as 12 hours between harvest and curing has been shown to be detrimental to successful curing.

Sweetpotatoes remain metabolically active after harvest. They respire, converting starch to sugars that are metabolized to release carbon dioxide and water vapor. Sufficient movement of air (ventilation) during curing is essential and helps dry roots and any adhering soil, provides proper oxygen and carbon dioxide exchange, and is necessary for good heat transfer during curing. As little as one-half cubic foot of outside air per bushel per day is sufficient for proper ventilation. However, sweetpotatoes injured by rough handling, exposed to chilling, or harvested from waterlogged soil may require as much as 5 to 10 cubic feet of outside air per bushel per day.

The humidity during curing should be as high as possible (85 to 90 percent) but not to the point where water may be seen on the walls, floors, bins, or especially the sweetpotatoes. All properly designed curing facilities should have correctly sized humidification equipment and controls. The cost of this equipment is easily recovered in reduced weight loss and better root quality. Curing rooms should be properly insulated to conserve energy and reduce condensation. (See Appendix 3 for a discussion of insulation materials.)

BENEFITS OF CURING:

1. Curing enhances culinary characteristics (eating quality). A sweetpotato's culinary characteristics are a combination of color, texture, taste, aroma, and fiber content. Much of the culinary character of an individual sweetpotato depends on the cultivar and, to a smaller extent, on cultural practices during the growing season. Some of the most important culinary characteristics, however, are the result of chemical changes that occur as a result of curing. Proper curing has been shown to increase the sensation of moistness and sweetness, enhance the aroma, and decrease starch content while increasing sugars.

2. Curing aids in wound healing and reduces losses due to shrinkage and disease. When roots are wounded, the exposed cells will quickly dry and die. Sweetpotatoes will naturally exude sticky latex from injuries, particularly at the ends of the sweetpotato (Figure 14). This material may dry in a few hours and appear to close the wound, but it actually provides little protection from decay organisms or weight

Figure 14. Latex stains on roots. PHOTO BY B. EDMUNDS

loss. Only proper curing can result in "true" wound healing. Under curing conditions, the sweetpotato will deposit a layer of material under the dead cells in the wounded area. This barrier further reduces moisture loss and impedes microbial invasion of the tissue. In the final stage of this process, a second layer similar to undamaged skin is deposited under the wound in a process known as *suberization*.

3. Curing sets the skin. Freshly harvested sweetpotatoes have thin, delicate skin that is easily broken, scraped, or otherwise removed (Figure 5). Some cultivars may be washed and graded without serious injury if it is carefully done within 24 to 48 hours of harvest. However, most cultivars require curing to "set the skin" because the skin quickly becomes too loose to permit safe handling. Proper curing after harvest results in skin that sets within four to six weeks. The exact time required for skin set varies considerably across cultivars. The factors influencing skin set, such as growing conditions, are not well understood and are the subject of ongoing research.

If roots must be shipped soon after harvest, the time required for skin set may be shortened somewhat by proper curing at standard conditions followed by several weeks at proper storage temperatures but at less than 85 percent relative humidity with good air ventilation (as much as 30 to 50 cubic feet of ventilation per day per bushel may be required in this circumstance). This treatment may allow roots to be shipped sooner but will result in increased weight loss, so it is important to move this product quickly to market. For longer storage periods, follow the curing period with normal storage conditions—55°F (13°C), 85–90 percent relative humidity, and adequate ventilation.

PROBLEMS ASSOCIATED WITH IMPROPER CURING:

Inadequate and excessive curing can shorten shelf life, increase sprouting during storage, and result in excessive weight loss. Normal weight loss should not exceed 5 to 8 percent of the freshly harvested weight.

Improper ventilation during curing can result in an extremely low oxygen/high carbon dioxide environment. Exposure to this environment for short periods has been shown to reduce the effectiveness of curing, shorten storage life, and alter the taste of the sweetpotatoes, but this problem is unlikely to occur in a properly operated modern facility.

Curing at improper temperatures or humidity can reduce quality during storage. Research has shown that curing sweetpotatoes at temperatures below 75°F (24°C) increases weight loss and decreases storage life. Low humidity also results in inadequate healing of wounds.

Curing that continues for too long can result in widespread sprouting (Figure 15). It is not unusual to see short (less than one-fourth inch) sprout buds on a few roots toward the end of curing; however, widespread sprouting results in rapid weight loss. The best way to minimize weight loss from overcuring is not to exceed the recommended three to five days of curing and to reduce the temperature to 55 to 60°F (13°C) as quickly as possible. Maintaining the correct relative humidity (85 to 90 percent) during storage is also critical.

Storing for Quality

The next step in the production of quality sweetpotatoes is storage in the proper environment. The primary goal of storage is to maintain root quality and ensure an adequate supply throughout the year by minimizing both physiological disorders and disease development. Current experience shows that high-quality roots that are properly cured and held, undisturbed, under proper storage conditions—55°F (13°C), 85 to 90 percent relative humidity, with adequate ventilation—remain marketable for as long as 13 months.

These storage conditions were first determined in the 1920s with cultivars grown at that time, and recent research has shown that these conditions are still valid for modern commercial cultivars. It is important to maintain the temperature as close as possible to 55°F (13°C). Minor fluctuations of three or four degrees are expected, but avoid fluctuations of more than five degrees. Fluctuations can occur when roots are stored in common storage or in a room without temperature regulation. Fluctuations of more than five degrees will lead to premature breakdown of the sweetpotato and excessive weight loss.

Higher relative humidity (greater than 85 percent) would be entirely suitable for sweetpotato storage. However, from a practical standpoint, very high humidity (90 to 95 percent) is difficult to maintain consistently and to measure accurately. Additionally, very high humidity will cause condensation to form on the building walls or roof, causing maintenance problems and the wetting of bins and roots, which promotes decay. Improper room insulation can also contribute to condensation problems.

PROBLEMS ASSOCIATED WITH IMPROPER STORAGE CONDITIONS:

Improper storage conditions can increase the development of physiological disorders and diseases. Physiological disorders are the result of stresses related to excessive light, heat, cold, and moisture, or the mix of surrounding gases such as oxygen, carbon dioxide, and various pollutants. Some disorders can be caused by mechanical damage, and all are abiotic in origin (not caused by disease organisms) and cannot be controlled by postharvest pesticides. However, many postharvest disorders compromise the sweetpotato's natural defenses, which in turn increases susceptibility to infectious postharvest diseases. In some cases, physiological disorders may even mimic infectious diseases. Common physiological problems resulting from improper storage conditions include excessive dry matter loss, sprouting, pithiness, hardcore, chilling injury, and moisture loss (Figures 9 through 11).

Dry matter loss and pithiness. Sweetpotatoes lose dry matter through natural respiration. Respiration is a chemical process necessary for all living tissue whereby starches and sugars (dry matter) are oxidized to carbon dioxide and water vapor with the liberation of heat. The heat generated by an individual sweetpotato is negligible, but the combined output of thousands of bushels in a storage facility can raise the temperature of sweetpotatoes one-fourth to one-third degree per day. This heat must be continually removed from

Figure 15. Sprouting due to poor curing or storage conditions. Note that sprouts generally originate from the proximal end of the root (i.e., the end closest to the plant). (PHOTO BY G. HOLMES)

the facility, or the temperature will rise above acceptable levels in a short time. A storage facility must have provisions for cooling with outside air or a refrigeration system.

Although not apparent externally, significant dry matter loss may result in pithiness with the formation of many small voids (Figure 10). Pithiness is very common in sweetpotatoes held for long periods in poorly controlled storage facilities.

Sprouting in storage. Another effect of elevated storage temperatures is sprouting (Figure 15). At temperatures above 60°F (16°C), sweetpotatoes will sprout. The length of time required for sprouting depends on the temperature. It may take a month or more for sprouts to show at 65°F (18°C), but at 75°F (24°C) and warmer, sprouts can develop in a few weeks. Sprouting is always accompanied by rapid respiration and weight loss. Chemical sprout inhibitors are not used in sweetpotatoes because proper temperature control inhibits sprouting. USDA standards (see Appendix 2) list sprouts over three-fourths of an inch long as defects. Sprouts can be manually removed from roots during the packing process.

Chilling injury. Chilling injury is rare in modern storage facilities, but it can occur if roots are kept in common areas during the winter months. Storage below 50°F (10°C) can result in chilling injury that may not be evident until several weeks have passed (Figures 9 through 11).

Excessive shrinkage. If the humidity is low, sweetpotatoes will lose weight as moisture evaporates from the surface of roots. This results in weight loss and may cause shriveling of the skin, especially at root ends (Figure 16). Although some moisture loss is practically unavoidable during curing and storage, excessive water loss may be avoided by maintaining high relative humidity during storage.

Figure 16. Weight loss is increased by skinned areas and leads to shriveling. (PHOTO BY B. EDMUNDS)

TABLE 1. Typical components and sequence of components in medium and large sweetpotato packing lines.

Medium (Low Volume) Packing Line	Large (High Volume) Packing Line
dump tank	dump tank
wash/brush	wash/brush
eliminator	eliminator
grading	grading
fungicide application	**wash/brush***
sizer	fungicide application
grading	sizer 1-expanding pitch type
box fill	first grading
	wax/brush*
	sizer 2-electronic*
	final grading*
	box fill

*Bold text indicates items that differ from medium packing lines.

Disease development in storage. By far, postharvest diseases account for the greatest loss in stored sweetpotatoes. In extreme instances, decay losses can run nearly 100 percent. The occurrence of postharvest diseases tends to vary from year to year. Outbreaks occur when pathogens are given an opportunity to proliferate. Many of the diseases that affect sweetpotatoes in storage are first established in the field or on planting material such as scurf (Figure 51). Other postharvest disease organisms are wind- or soil-borne as spores and are essentially ubiquitous (such as Rhizopus soft rot).

Postharvest diseases may be caused by fungi, bacteria, or viruses, although fungi are more common in sweetpotatoes. Most viruses do not cause serious postharvest diseases, although symptoms from field infections may be first noticed after harvest (as with russet crack) or may develop in storage (internal cork). Similarly, root knot nematodes infect roots in the field, and the resulting cracking may be noticed during grading and packing (Figures 54 and 55).

Control depends on understanding disease-causing organisms, the conditions that promote their occurrence, and the factors that affect their capacity to cause losses. Additionally, following approved cultural practices in the field can significantly reduce many of these diseases. Sweetpotatoes should be inspected as they are harvested. Leave roots with indications of established disease (lesions) or obvious defects such as growth cracks or excessive skinning in the field. Gentle handling and minimization of environmental stresses can substantially reduce the level of postharvest disease. The management of specific diseases is discussed in Appendix 1.

Packing for Quality

The packing of sweetpotatoes is an industrial operation that should be dedicated to delivering the highest quality product to the consumer. The current market demands uniformity in appearance in both color and size (see cover photo bottom), which necessitates long and complicated packing lines. Unfortunately, long packing lines can increase the opportunity for skinning, bruises, cuts, and broken ends that detract from appearance and increase the possibility for disease development.

In general, good packing-line design strikes a balance between gentle, yet efficient, handling of the sweetpotatoes. Indications of the need to alter an existing packing line include high labor and energy costs, bottlenecks, congestion, worker complaints, accidents, and product damage such as excessive skinning, excessive loss to disease, and large piles of broken ends on the floor below problem areas.

An industry survey of sweetpotato packinghouses in North Carolina and Louisiana from 2004 to 2006 revealed similarities among layouts and associated trouble spots (Tables 1 through 5). Table 1 describes the typical components and layouts for mid- and large-size packing lines

Figure 17. Instrumented impact recording device used to measure impacts on packing lines. Right: fresh sweetpotato; middle: molded urethane casing with accelerometer inside; left: handheld computer with antenna for receiving signal from accelerometer and recording impacts. PHOTO BY B. EDMUNDS

seen in both states. An instrumented impact-recording device (SmartSpud, Sensor Wireless, Canada) was used on packing lines in both states. This device measures the force of impacts (measured as a unit of force called a g; 1 g = 9.81

Figure 18. Dumping roots using a forklift-mounted bin rotator device. (PHOTO BY G. HOLMES)

Figure 19. Dumping roots using an automatic bin rotator. (PHOTO BY G. HOLMES)

Figure 20. Dump tank with metal bib to sift out soil. (PHOTO BY G. HOLMES)

Figure 21. In a submerged dump, the entire storage bin is placed in the dump tank, and roots float out. (PHOTO BY G. HOLMES)

meters/second squared) with higher numbers indicating areas or drops on packinglines where potentially damaging impacts are occurring. The original device used by researchers was called an *instrumented sphere* because of its shape, and a major improvement has been the development of a urethane or silicon casing that mimics the dimensions of the commodity being tested. The North Carolina State University engineering department fabricated a casing by making a mold of an actual sweetpotato (U.S. No. 1 grade, Figure 17). This casing allows for measurements that reproduce impacts received by sweetpotatoes on a packing line. Impacts occurring at specific points on the packing line will be discussed further and are summarized in Tables 2 and 4.

Dump Tank. Sweetpotatoes are generally dumped into a tank of water (dump tank) either by a bin rotation device on a forklift (Figure 18) or an automatic bin rotator (Figure 19). Because harvested roots go directly into storage without washing, sweetpotatoes always have significant amounts of soil adhered to the surface, even when harvested from dry, sandy soil. Some dump tanks have a bib of small metal bars that sift the loose soil out as the roots tumble into the dump tank (Figure 20). The bib prevents some of the soil from entering the water, but the impact of the roots on the bars is high and is also a major source of mechanical injury. Skinning is particularly severe because dry roots skin much easier than wet roots. Because the severity of damage is directly related to the distance of the fall, automatic bin rotation equipment (which shortens the fall distance) is preferred to bin rotators on forklifts. A better option is an automatic bin rotator with a lid, which gradually releases the roots into the dump tank and minimizes root-to-root impacts. The best option for minimizing root injury is the "submerged dump" (Figure 21). This requires specialized equipment that completely submerges the entire bin into a water tank, allowing the roots to float out and virtually eliminating root-to-root impacts. Submerged dumps have yet to be adopted in the Southeast mainly due to the expense associated with the equipment and the transition to plastic storage bins. (Wooden bins quickly break down when wet and are poorly suited for this type of dump.)

Figure 22. High-volume water rinse is used to clean roots. (PHOTO BY B. EDMUNDS)

Figure 23. Eliminator on a packing line. Roots smaller than 1.5 in (3.8 cm) in diameter fall through the bars. (PHOTO BY G. HOLMES)

Figure 24. Proper lighting and height for grading table allows workers to adequately see and reach cull roots. (PHOTO BY G. HOLMES)

The dump operator can have a major influence on impacts. Operators must be able to see into the dump tank so that they can carefully monitor the dumping operation. Sweetpotatoes should not be dumped into an overfilled tank, which causes excessive impacts.

Unloading sweetpotatoes into the dump tank generates a large amount of dust. In addition to creating problems for workers and machinery, this dust usually contains decay-causing spores that are a ready source of contamination for nearby sweetpotatoes. For these reasons, it has become customary to partition or wall off the dump tank from the rest of the packing line. Additionally, ventilation fans should be installed near the dump tank to draw the dust outside the building and away from the rest of the line. Fans also help keep dust away from forklift and dump operators.

Dump tanks vary in size but may hold several thousand gallons of water. A portion of this water is flushed regularly, along with the heavier soil, through a large, air-operated slide or butterfly valve located on the bottom of the tank. The air cylinder may be switched on manually or activated by a simple float switch and timer circuit. Many newer dump tanks also have automatic monitors that adjust the water level as needed.

To reduce decay, some packers treat the dump tank water with antimicrobial agents. Sodium hypochlorite (liquid bleach) is commonly used. Unfortunately, bleach is quickly deactivated by large amounts of soil in dump tanks and must be recharged at regular intervals (dependent on the amount of soil entering the dump tank). The gases released from treated dump tanks can irritate the skin and eyes of workers and corrode metal surfaces. Very high concentrations of bleach in dump tanks may also lead to root bleaching. Other treatments that have been used with limited success include ozonation and copper ionization. Although these treatments may kill pathogens in relatively clean water, suspended soil particles diminish their efficacy, making them impractical on packing lines. Several studies have shown that sanitizers are not effective for controlling Rhizopus soft rot.

Washing. Most sweetpotato packing lines use a water rinse step to remove clinging soil. Waterfall/curtains and normal- or high-pressure spray washers may be used (Figure 22). High-pressure washers have become popular because of the difficulty of removing darker soils from some sweetpotato cultivars. Water at pressures as high as 250 pounds per square inch (psi) is directed by spray nozzles at the surface of sweetpotatoes as they travel over rotating brushes.

The dump tank and spray washer can use several thousand gallons of water per hour. Even if a well or other source can supply this amount of water, packing line operators should consider disposal: The less water a packing line uses, the less that needs disposal. For this reason, many sweetpotato packing lines have screens and tanks to collect the water from the wash step and use it to supply the dump tank. This simple plumbing arrangement can reduce water use (and disposal) by two-thirds or more.

Impacts are generally low during washing because most packing lines wash over a brush bed. Some brush beds are immediately preceded by a metal incline, which itself can be a source of high impacts.

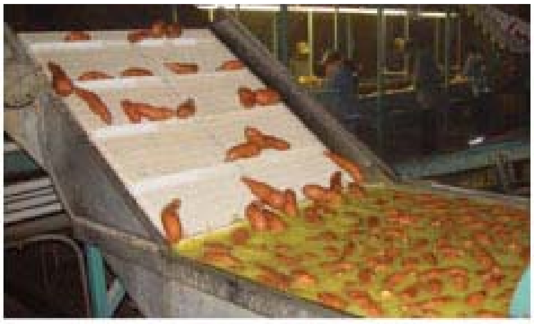

Figure 25. A dip tank can be used to apply fungicides (PHOTO BY G. HOLMES)

Figure 26. Fungicides may also be applied by using a waterfall/curtain. (PHOTO BY G. HOLMES)

Figure 27. Spray application over a brush bed is a common method of applying fungicides. (PHOTO BY G. HOLMES)

Eliminator. Most packing lines have one eliminator. (Less than five percent have two.) The eliminator consists of a bed of parallel metal rollers normally set 1.5 inches (3.8 cm) apart (Figure 23). The eliminator quickly removes trash and small unmarketable roots. It is important that the roller spacing does not get dented or bent, as this will increase the spacing and cause marketable roots to be discarded. Impacts can be severe if sweetpotatoes fall directly onto the rollers, rather than rolling down an incline onto the eliminator, because the rollers are supported by the chain guides.

Instrumented device readings averaged 8.8 g and ranged from a low of 0 g where the sweetpotatoes rolled down a gentle incline (total drop of 5 inches) to a high of 30.7 g in a case where the sweetpotatoes fell about 16 inches directly onto the eliminator rollers.

Grading. After washing and elimination of trash, sweetpotatoes move onto a table for hand sorting and removal of decayed or otherwise unmarketable roots. The tables are generally made of PVC rollers and should be easily accessible by workers from both sides (Figure 24). Adequate lighting is important, so that defects can be seen easily. Table height should also allow workers to reach roots in the middle of the table comfortably. Workers who directly handle roots should wear gloves to protect roots from fingernail scratches and human pathogens. Gloves will also protect workers from fungicides or other chemicals used on the packing line.

Impacts on the grading line vary, depending on height of the drop and whether there was an incline or padding. For example, one packing line had a drop height of only 3.5 inches, and the impacts were all below the threshold recorded by the instrumented device. On the other extreme, another packing line had roots dropping 12 inches directly onto the rollers, which produced a much higher impact (23.5 g).

Fungicide and other decay control treatments. Although every effort should be made to prevent mechanical injury to sweetpotatoes during packing, it is impossible to avoid all injuries. Decay-producing organisms, especially those that cause soft rot (such as *Rhizopus stolonifer*), enter through injuries. Bruised or crushed tissue offers a particularly favorable place for decay to develop. For this reason, most sweetpotatoes not destined for canneries or further processing are treated with an approved fungicide.

TABLE 2. Average number of drops and turns, cumulative impacts, and length of packing lines, based on 24 Louisiana and 12 North Carolina packing lines.

	Average	Maximum	Minimum
Number of drops	10	19	5
Number of turns	3	8	0
Cumulative impacts (g)*	118	302	31
Length of line (ft)	102	277	37
Speed of line (ft/min)	24	59	7

*Cumulative impacts measured on all drops and turns on a packing line. Average of five runs with the impact recording device.

Figure 28. Roots falling out of an expanding pitch roller (EPR) sizer usually land on the root end. (PHOTO BY G. HOLMES)

Figure 29. Overlapping roots (shown inside yellow circle) on an electronic sizer leads to placement on the return loop of the packing line. (PHOTO BY G. HOLMES)

Fungicide may be applied either by dipping the roots in a tank of chemical suspension (Figure 25), by using a waterfall/curtain application (Figure 26), or by spraying the fungicide either alone or mixed in a wax solution as the sweetpotatoes pass over a brush roller conveyor (Figure 27). Regardless of treatment method, roots must be completely covered with the fungicide suspension. No treatment is 100 percent effective. Even properly treated roots may develop significant decay. For specific recommendations on the use of fungicides, refer to the manufacturer's label instructions, state Extension manuals (such as *North Carolina Agricultural Chemicals Manual* or *Louisiana Plant Disease Management Guide*), or contact your local Extension center for guidelines in your state.

Sizing. Sorting sweetpotatoes into uniform sizes is a key function of packing. The U.S. sweetpotato grade standards for both fresh market and canning were updated in 2005 and are found in Appendix 2. Most mid-size sweetpotato packing lines employ expanding pitch roller (EPR) sizers. These sizers allow the roots to move along on a conveyor of rotating and ever-widening rollers. The smaller roots are the first to fall between adjacent rollers and are deposited on a belt moving perpendicular to the direction of the rollers (Figure 28). Larger roots are carried further before they are deposited to a different section of the belt. EPR sizers segregate sweetpotatoes only by diameter. Sweetpotatoes with the same diameter but different lengths will be placed in the same category. Unless there are large variations in root lengths (usually a function of cultivar and growing conditions), EPR sizers satisfy most commercial U.S. grade requirements.

As there is an increasing demand for more uniformity both in diameter and length, high-volume packers have invested in electronic sizers that optically scan both length and diameter and segregate sweetpotatoes into precise grades. If overlap (Figure 29), abnormal shape, or color prevents the sizer from categorizing a root properly, it will travel to the end of the sizer and go through a "return loop" to be resized. As much as 30 percent of roots have been observed going through this return loop. With this in mind, consideration must be given to the drop heights and speed of the conveyors on these return loops, because skinning

TABLE 3. Average decay control product use and application methods, averaged over 22 Louisiana and 21 North Carolina packing lines.

	Percent of Packing Houses	
	Louisiana	North Carolina
DECAY CONTROL PRODUCT USED		
Dicloran (Botran)	77-91*	81
Other (peracetic acid, bacteria-based biological control)	5-18*	9.5
None	5-9*	9.5
APPLICATION METHOD		
Spray	50	32.5
Curtain	0	4.5
Dip	45	42
In wax	0	21

* Several packing lines used different products one time to another.

Figure 30. Box fill can occur off the end of a conveyor. (PHOTO BY T. SMITH)

Figure 31. Automatic box fillers are integrated into electronic sizing equipment. (PHOTO BY G. HOLMES)

and bruising can be significant. Furthermore, a significant portion of roots may pass through a return loop more than once. Many high-volume packers employ both an expanding pitch sizer and an electronic sizer to size roots efficiently into the correct grade.

Impacts depend on the height of the drop, whether there is an incline onto the sizer, and whether there is padding. Impact measurements were quite low on lines where the sweetpotatoes rolled down a gradually padded incline onto the sizer, and were higher on a few lines where there was a high drop directly onto sizer bars.

Box fill. Boxes (40 and 14 lb) can be filled by hand in small operations (Figure 30). Mid-size and large packing lines generally fill boxes by allowing the roots to fall off a conveyor into the box or by using an automated box fill system (Figure 31). Automated systems are mainly used with electronic sizers. These devices are able to control the speed of roots entering the box, may have a hydraulic tilt mechanism that automatically lowers the box as it fills, and will release boxes when they have filled to the designated weight.

Most box fills are a similar height, so any variation in impact measurement (Table 4) is related to how full the box was at the time of measurement. Roots dropping into an empty box will experience larger impacts than those dropping into an almost full box. In the survey, higher impacts were found with automatic box fillers, which may be due to the greater height of the drop or the speed of the conveyor filling the boxes. Impacts from specialized packing (plastic or net bagging machines) were also measured and can be high if large-distance drops are present.

Reducing Packing Damage

Mechanical damage to sweetpotatoes during handling may include cuts, abrasions, and bruises, depending on the physics and configuration of the surfaces involved. A survey of 46 Louisiana and North Carolina sweetpotato packing lines from 2004 to 2006 provided valuable insight into ways to limit damage during packing. This study concluded that significant differences exist among various packing line configurations and even within the same line operated at different capacities and speeds.

Other significant findings indicate that most damage to roots occurs from impacts between roots and the various surfaces of the packing line. This suggests that cushioning these surfaces or otherwise reducing impacts may significantly reduce mechanical damage to the roots. Common "make do" padding materials, such as carpet and upholstery foam, perform poorly when compared to specially engineered padding materials but are, nevertheless, much better than bare metal surfaces. Use a good-quality cushioning material on all impact surfaces. The best material for cushioning is one that absorbs the energy from the falling root, so obtain samples from the manufacturer and test energy absorbency by dropping a root onto the samples. A material that has less bounce is a better material for padding sweetpotato packing lines because the roots won't rebound and hit another packing line surface. The ideal cushioning material should also have a tough surface that resists wear and doesn't absorb water and dirt. Padding material should be easy to wash during packing line cleanings. Carpet materials fail in this regard because they absorb water and soil and are difficult to clean.

Keep packing lines as level as is practical. Packing lines that continually raise and lower the roots impart potential energy that results in mechanical damage. For example, when sweetpotatoes are elevated by a belted conveyor or other means, potential energy is imparted, which is proportional to the height raised. When sweetpotatoes are allowed to fall or roll back to the lower level, the potential energy is changed into kinetic energy (motion), which must be absorbed by the roots or some impact surface.

Figure 32. Install velocity-reducing flaps to slow root speed over packingline drops. (PHOTO BY G. HOLMES)

Figure 33A-C. Avoid very steep drops onto unpadded hard surfaces. (PHOTOS BY G. HOLMES)

When sweetpotatoes must be lowered from one level to another, do so gently by using generous quantities of energy-absorbing blankets, strips (Figure 32), or padded surfaces. Long, inclined surfaces will reduce velocity better than near-vertical falls. Conveyor belts have minimal energy-absorbing ability. When sweetpotatoes are allowed to drop onto a belt supported by sheet metal or rollers (for example, under a sizer), the level of bruising is nearly the same as if the belt were not there. If possible, remove the supports to allow the belt to be suspended, providing an energy-absorbing impact surface.

Synchronize packing and grading line components to prevent abrupt changes in velocity or direction of the produce. Carefully engineer cross conveyors to include curved and padded transitions that allow a gradual change in direction and velocity. Operate packing lines no faster than necessary to reduce root damage and wear on the components.

Recommendations to reduce damage on packing lines

- Dump roots slowly into water (not onto roots) in the dump tank.
- Use high-quality padding on all impact surfaces.
- Use long inclines to reduce drop heights between components (Figure 33A through C).
- Reduce the number of drops and turns (Figure 34).
- Reduce the overall length of the packing line.
- Remove belt supports (if feasible) to reduce impact.
- Use deceleration flaps and blankets to reduce the speed over drops.
- Instruct workers to handle roots with care, and monitor handling frequently.
- Avoid abrupt changes in direction and speed of belts. Add padding if turns are unavoidable.
- Reduce packing line speed.

Figure 34. Packing line turn without padding. Note worn paint where roots make contact with metal guides. (PHOTO BY B. EDMUNDS)

TABLE 4. Impact measurements associated with common drops on sweetpotato packing lines, averaged over 23 Louisiana and 12 North Carolina packing lines.*

Components/Transfer Point	Average Cumulative Impact (g)	Maximum	Minimum	Number Surveyed
DUMP				
By hand	6.8	7.1	5.1	1
Onto bars (dry dump)	13.0	17.3	8.7	2
Into tank w/ metal lid	13.0	22.9	5.4	3
Directly into tank	12.8	36.1	0	29
MISCELLANEOUS				
Onto eliminator (metal bars)	8.8	30.7	0	27
Onto grading line (PVC bars)	8.3	29.2	0	40
Onto brushes	8.2	35.9	0	58
Onto conveyors (plate supported)	9.6	35.4	0	34
SIZERS				
Onto EPR** sizer	17.7	30.6	4.5	29
Out of EPR sizer (onto conveyor)	14.1	34.2	4.6	29
Onto drop-roller sizer	19.2	25.7	10.1	1
Out of drop-roller sizer (onto conveyor)	5.8	13.3	0	1
Electronic sizer	21.6	53.8	4.6	5
BOX FILL				
By hand or falling off conveyor	12.4	39.5	0	30
Automated box filler	30.3	72.5	4.2	6

*Average of five passes with the instrumented impact recording device
**EPR=expanding pitch rollers

Packing Line Cleaning and Sanitation

No matter how careful the operation, decay-producing organisms enter the packinghouse with the sweetpotatoes and will quickly contaminate all working surfaces. These organisms can remain viable for many months on storage bins, tank walls, sorting belts, rollers, and brushes. It is possible for surfaces to remain contaminated from one packing session to the next, or in the case of storage bins, from one year to the next.

Some pathogens that cause significant postharvest diseases of sweetpotato, such as *Rhizopus*, are common everywhere, and it is not possible to eliminate them completely. However, the amount of contamination is often important in determining whether disease develops. Thus, reducing the amount of contamination is the general aim of cleaning and sanitation efforts.

Reducing the introduction of pathogens onto the packing line. On most sweetpotato packing lines, roots are dumped into a tank of water and then fed onto the rest of the line. This process often spreads disease-causing microorganisms. Thus, reducing the amount of disease that develops in storage will reduce the number of diseased roots that enter the dump tank and contaminate the packing line. The following are a few important considerations for reducing disease development in storage:

TABLE 5. Percent of packing lines that use a technique or have each type of component, based on 25 Louisiana and 21 North Carolina packing lines.

	Percent of Packing Houses	
	Louisiana	North Carolina
DUMP		
By hand	0	9.5
Onto bars then into dump tank	0-8*	9.5
Directly into dump tank	84-92*	81
Onto rollers (dry dump)	8	0
MISCELLANEOUS COMPONENTS		
Eliminator	56	75
Waxer	0	57
Drying fans	0	43
SIZERS		
No sizing equipment	12	9.5
1-2 EPR** sizers only	84	62
Electronic sizer only	0	19
Drop-roller sizer only	4	0
Both EPR sizer and electronic sizer	0	9.5
BOX FILLERS		
Automatic box fill equipment	0	28.5
Box fill from off end of conveyor	96-100***	62
Box fill by hand picking	0-4***	9.5

* Two packing lines have movable sets of rollers that are used only when roots are muddy; otherwise, roots are dumped directly into the dump tank.
**EPR=Expanding pitch rollers
*** One line hand picks sometimes and lets them fall from end of conveyor other times.

CLEANING VS. SANITATION

CLEANING: the removal of debris from packing line surfaces using physical methods such as high-pressure water sprays or a detergent.

SANITATION: the reduction of the number of microorganisms on packing line surfaces to levels that do not cause disease problems.

- **Extreme field conditions at harvest:** Extreme environmental conditions at harvest can increase disease development in storage. Very dry soil increases skinning of the roots, a problem in itself, and can also favor Fusarium root rot. The other extreme, flooded soils, can contribute to the complex condition of souring that leads to simultaneous increases in many diseases, including Rhizopus soft rot, bacterial soft rot, Fusarium root rot, and sour rot. Flooding also results in mud adhering to the sweetpotatoes and being carried into storage. Anything that can be done to avoid extremely dry or wet conditions at harvest will reduce problems in storage.
- **Sanitation of storage bins:** Bins that can hold in excess of 20 bushels of sweetpotatoes are likely to have at least a few roots that develop disease during a long storage period. Assume that they are all contaminated after use. Cleaning and sanitizing the bins after each use should be a regular practice. Spotts and Cervantes (1994) studied disinfestation of wood and plastic surfaces used in bins for storing pears. They found that steam was the most effective in reducing populations of fungi that infect pears. Chlorine compounds, sodium orthophenylphenate (SOPP), and quaternary ammonium compounds were also effective but were less consistent than steam. Most of these agents were similarly effective on wood and plastic except sodium hypochlorite, which was less effective on wood. Leaving the bins outside in the summer, where the surfaces that contact sweetpotatoes are exposed to direct sunlight, may also help reduce microbial contamination.
- **Reducing disease development in storage:** Following the recommendations for proper curing and storage of roots remains one of the most effective ways of reducing diseases in storage. See the "Curing for Quality" and "Storing for Quality" sections for specific guidelines.

A single root affected with Rhizopus soft rot can produce millions of fungal spores. Likewise, a single root affected with bacterial soft rot can release millions of bacterial cells. Since both Rhizopus soft rot and bacterial soft rot can completely rot a sweetpotato in a few days, it makes sense to remove all roots that fall off the packing line from the packing area at the end of each day. Otherwise, they will quickly become a source of inoculum that can infect healthy roots.

Cleaning and Sanitation. No matter how rigorous your disease-control efforts are, some diseased roots will go into the packing operation, and there will be a need to clean and

TABLE 6. Guidelines for mixing chlorine solutions*

Desired ppm of Free Chlorine	Pints of 5.25% NaOCl Solution per 100 Gal. of Water	Pints of 12.75% NaOCl Solution per 100 Gal. of Water	Ounces of 65% Ca (OCl)2 per 100 Gal. of Water
50	0.8	0.3	1.0
75	1.1	0.5	1.5
100	1.5	0.6	2.1
125	1.9	0.8	2.6
150	2.3	0.9	3.1
175	2.7	1.1	3.6
200	3.0	1.3	4.1

*From "Chlorine Use In Produce Packing Lines" Document HS-761 Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, and used with the permission of the authors.

sanitize the packing line. Regardless of what surface is being sanitized or what agent is used for sanitizing, it will be more effective if the surface is cleaned first. Some microorganisms form biofilms (a microscopic layer of bacteria) that are particularly difficult to remove. Removal of biofilms requires detergent and pressure, either from scrubbing or from a pressure washer. In order to properly sanitize surfaces, the following sequence should be followed:

Rinse → Clean → Rinse → Sanitize

Nonporous and exposed surfaces may be relatively easy to clean and sanitize, but other components of the packing line may require special attention. Of particular concern are the brush beds. Small bits of debris and tissue broken from sweetpotato roots may become lodged at the base of the brush bristles and support the growth of microorganisms. High-pressure hoses or a pressure spray will flush debris out of the brushes.

There are no uniform standards in the sweetpotato industry for sanitizing packing lines, and the effect of sanitation on postpacking disease development is not known. Some packers have relied on chlorine, primarily sodium or calcium hypochlorite, without understanding the factors that influence its efficacy. In water, the most commonly used forms of chlorine that are used for sanitizing (sodium hypochlorite, calcium hypochlorite, or chlorine gas) all form hypochlorous acid. Hypochlorous acid is the component that kills microorganisms and is referred to as *available* or *active* chlorine. At high pH, hypochlorous acid dissociates to form a hypochlorite ion, which is not effective as a sanitizer, and chlorine solutions with a pH above 8 are not effective in killing pathogens. Below pH 6, chlorine solutions are highly corrosive, and the activity is rapidly lost due to volatility of elemental chlorine. The volatile chlorine can also irritate workers. Thus, in order to have an effective sanitizing solution, it is necessary to measure both chlorine content and pH and maintain the pH between 6.5 and 7.5.

Organic matter inactivates hypochlorous acid and reduces the amount of available chlorine. Even though the chlorine combined with the organic matter is inactivated, it is still measured by "total chlorine" test kits. This makes it difficult to maintain an effective chlorine solution in a dump tank where large volumes of soil and organic material enter. Chlorine must be added frequently to replace the chlorine lost. For produce harvested above ground, checking and replenishing the chlorine supply at least once an hour is often recommended. But a root crop introduces much more soil into the system, so the chlorine must be replenished more frequently. Generally, chlorine should be maintained at 100 to 150 parts per million (ppm) *active* chlorine with pH maintained between 6.5 and 7.5. Thus, chlorine test kits that measure active or available chlorine should be used. You may need to dilute the source product in distilled water for proper readings. Commercial systems that automatically monitor and adjust pH and chlorine are likely to be more effective in maintaining effective sanitizing conditions. Always follow the label directions for any product used.

Water temperature and water quality can also affect the efficacy of chlorine. For example, chlorine solutions are more effective at higher temperatures, but the chlorine is lost faster. Registered formulations of chlorinators for use on produce contain either 5.25 percent or 12.75 percent sodium hypochlorite (NaOCl), or 65 percent calcium hypochlorite [Ca(OCl)2]. To estimate the amount of these formulations to use in making chlorine solutions with various concentrations of free chlorine, use Table 6. Current research does not suggest that chlorine can be used for disease control. It should only be considered a sanitizer of water and equipment. Also, check current guidelines, as some products may not be acceptable by certain markets.

One additional problem with these chlorine products is that they produce trihalomethanes when they react with organic matter. These compounds are carcinogens and pose a potential health risk. Chlorine dioxide gas circumvents this problem because it does not react with organic matter to form trihalomethanes. Chlorine dioxide is also active over a wider range of conditions than other forms of chlorine and is an effective sanitizer. However, its use is not without problems, as the gas must be generated on site. When used indoors, adequate ventilation is essential because some of the gas can come out of solution.

As indicated earlier, there has been little research on sanitizing sweetpotato packing lines. However, several classes of chemical sanitizing agents have been considered for other perishable produce. There are many factors to consider when choosing a sanitizer, in addition to whether it will effectively reduce the number of pathogens. Many sweetpotato packers have experience with the corrosive nature of chlorine, and several have had to rebuild their packing lines because of this problem. Table 7 compares the properties of some of the classes of chemical sanitizers.

General recommendations for packinghouse sanitation: Fresh sanitizing solutions should be prepared and used daily. For sanitizing wash water, it is recommended that active (not total) chlorine levels be kept between 100 to 150 ppm, and the water pH should be kept between 6.5 to 7.5. The wash water should be replaced as often as possible during the day, or at least when it becomes obviously dirty. The frequency that wash water is replaced depends on the soil load, packing line configuration, and regulations regarding disposal, and it is specific to each packing line. Storage bins and packing line components should be cleaned and sanitized after each use, and sweetpotato roots and debris should be removed from the packinghouse floor daily.

Product Safety and Certification Programs

At the time of publication, no cases of foodborne illness associated with consumption of unprocessed sweetpotatoes have been reported in the U.S. In our rapidly changing environment, with increasing concerns for food safety, standards in addition to those listed may be required by different certifying organizations or markets.

Food safety has always been a concern and an important issue related to both domestic and international food supplies. In the 1990s, through the U.S. Produce Safety Initiative, the focus increased to ensure the safety of the nation's food supply, whether grown domestically or internationally. As a result, the U.S. Food and Drug Administration (FDA) developed guidelines for the produce industry with an overall goal of minimizing microbial food safety hazards. Those guidelines, known as Good Agricultural Practices (GAP) and Good Manufacturing Practices (GMP), have become increasingly important in the produce industry.

Growers use GAP and GMP extensively to improve and ensure the safety of their produce. Growers also are reducing risks to fresh fruits and vegetables with comprehensive education and traning programs on farms. GAP guidelines are primarily associated with production field practices, whereas GMP guidelines are aimed at storage and packing facilities.

As a first step in the certification process, all sweetpotato producers should register with the FDA, after which they will be issued a federal identification number. Producers can access the FDA's GAP and GMP guidelines online at http://www.cfsan.fda.gov/~dms/prodguid.html.

Producers who use the FDA guidelines are not only protecting the health of consumers, but are also reducing their financial risk. Participating producers are audited,

TABLE 7. Comparison of the chemical and physical properties in commonly used sanitizers.*

	Chlorine	Iodophors	Quaternary Ammonium Compounds	Acid Anionic	Fatty Acid	Peroxyacetic Acid
Corrosiveness	yes	slightly	no	slightly	slightly	slightly
Irritating to skin	yes	no	no	slightly	slightly	no
Effective at neutral pH	yes	depends on type	in most cases	no	no	yes
Effective at acid pH	yes, but unstable	yes	in some cases	yes, below 3.0 to 3.5	yes, below 3.5 to 4.0	yes
Effective at alkaline pH	yes, but less than at neutral pH	no	in most cases	no	no	less effective
Affected by organic material	yes	moderately	moderately	moderately	partially	partially
Affected by water hardness	no	slightly	yes	slightly	slightly	slightly
Residual antimicrobial activity	none	moderate	yes	yes	yes	none
Cost	low	high	moderate	moderate	moderate	moderate
Incompatibilities	acid solutions, phenols, amines	highly alkaline detergents	anionic wetting agents, soaps, and acids	cationic surfactants and alkaline detergents	cationic surfactants and alkaline detergents	reducing agents, metal ions, strong alkalies
Stability of use solution	dissipates rapidly	dissipates slowly	stable	stable	stable	dissipates slowly
Maximum level permitted by FDA without rinse	200 ppm	25 ppm	200 ppm	varied	varied	100 to 200 ppm
Water temperature sensitivity	none	high	moderate	moderate	moderate	none
Foam level	none	low	moderate	low to moderate	low	none
Phosphate	none	high	none	high	moderate	none
Soil load tolerance	none	low	high	low	low	low

*Comparisons made at approved "no rinse" use levels. *Adapted from B.R. Cords and G.R. Dychdala (1993) and R.H. Schmidt (2003), and used with the permission of the authors.*

inspected, and validated by an independent third party. These companies provide a checklist to growers that they will use to complete the auditing and inspection processes associated with certification.

Producers, packers, and shippers must comply with 70 percent of the guidelines to pass certification. Certain conditions are mandatory and can result in certification failure if they are detected. Examples include the determination of an immediate food safety risk, a violation of the U.S. Environmental Protection Agency (EPA) or state pesticide regulations, and failure to test or treat water sources. Two critical components of GAP and GMP involve educating employees and maintaining facilities. Producers should stress personal hygiene and ensure that all employees are provided a copy of safety guidelines. Employees working in a packing facility should not wear jewelry or body adornments, and they should also wear hairnets. It is also extremely important that sanitary facilities be provided to employees to promote personal hygiene and sanitary activity, such as frequent hand washing. Communication and cooperation between a producer and his or her production and packing employees is essential for GAP and GMP guideline compliance.

There is increasing interest in exporting sweetpotatoes produced in the U.S. to other countries, especially to Europe and the United Kingdom. At the same time, there have been rapid changes in laws, regulations, and attitudes of consumers and all levels of the produce-marketing industries regarding produce quality and pesticide residues. GlobalGAP is a third-party certification program with guidelines and standards that are used widely by fruit and vegetable producers and shippers in Europe and around the world for the voluntary certification of good agricultural practices. Specific information can be obtained from the GlobalGap Web site (http://www.globalgap.org/).

Packaging and Shipping for Quality

PACKAGING FOR QUALITY:

Proper packaging is an important step in the journey from packer to consumer. Packing and packaging materials constitute a significant cost to the sweetpotato industry; therefore, it is important that packers and shippers have a clear understanding of the different packaging options and their limitations. A significant percentage of produce buyer and consumer complaints may be traced to inferior container design or inappropriate container selection and use. A properly designed sweetpotato container will contain, protect, and identify the sweetpotatoes, satisfying everyone from grower to consumer.

The container must enclose the sweetpotatoes in convenient units for handling and distribution. Sweetpotatoes are now marketed in a variety of packages, depending on the requirements of the market (Table 8, Figures 35 A through F). Although the most common shipping size is the 40-pound carton, in recent years, the trend has been toward smaller packages designed to be carried home by the consumer.

All packaging containers must protect the sweetpotatoes from mechanical damage and environmental conditions during handling and distribution. Torn, dented, or collapsed packages usually indicate lack of care in handling. Sweetpotato containers must be sturdy to resist damage during packaging, storage, and transportation to market. Because almost all sweetpotato packages are palletized, the container must have sufficient stacking strength to resist crushing in a high-humidity environment. Although the cost of packaging materials has escalated in recent years, inferior quality, lightweight containers that are easily damaged by handling or moisture are no longer tolerated by packers or buyers.

The package must also identify and provide useful information about the contents. It is customary (and may be required in some cases) to provide information such as produce name, brand, size, grade, cultivar, net weight, count, fungicide treatment, grower, shipper, and country of origin. It is also becoming more common to include nutritional information, recipes, and other useful information directed specifically at the consumer.

The federal government now requires that records be kept on all sweetpotatoes packed. Currently a "one step forward, one step back" approach is being enforced. This means that packers must keep track of the source of the roots as well as the shipping destination. Traceability is the ability to follow a piece of produce from the grower through consumption. Traceability of individual containers and pallets of produce in general is a system undergoing improvements. Current guidelines on the implementation of produce identification and traceability can be found on the Produce Marketing Association's Web site (www.pma.com).

SHIPPING FOR QUALITY:

It is estimated that as much as 5 percent of packed sweetpotatoes are lost annually during transportation to market. Much of the loss is a direct result of mishandling during shipment. To reduce losses, shippers, truckers, and receivers should be well acquainted with the specific handling requirements of sweetpotatoes.

Packaged and palletized sweetpotatoes awaiting shipment should be refrigerated at 55°F (13°C) and 85 percent relative humidity immediately after packing. This storage area should be separate from the area where unwashed roots are stored and, ideally, near the loading dock.

Exercise care when storing or shipping sweetpotatoes with other commodities. Packed sweetpotatoes usually are shipped to domestic and Canadian markets in tractor-trailers, which may be loaded with other commodities. The two main concerns when cross-loading are compatibility between ethylene sensitivities and required storage temperatures. Ethylene is a naturally occurring, odorless, colorless gas produced by many fruits and vegetables, but it can also be produced by faulty heating units and combustion engines. In sweetpotato, ethylene damage is difficult to diagnose but can cause internal darkening and pithy areas. Sweetpotatoes are low emitters of ethylene when stored and handled properly, but they may produce higher levels of ethylene when wounded, infected, or subjected to chilling injury. Sweetpotatoes are considered to be sensitive to the ethylene produced by other commodities and machinery, so avoid shipping in mixed loads with ethylene-producing commodities. Most ethylene-producing commodities are shipped at much lower temperatures than sweetpotatoes; however, avoid mixing loads with bananas, mangoes, papa-

TABLE 8. Types of packaging for sweetpotatoes

Corrugated Fiberboard	The most common container material. Available in many different styles and weights. Relatively low in cost and easy to print with customized labels. Most 40-pound boxes are one-piece, regular slotted containers (RSC) and two-piece, full telescoping containers (FTC). The RSC is the most popular because it is simple and economical. However, the RSC has relatively low stacking strength and therefore is most often used with produce (for example, sweetpotatoes) that can carry part of the stacking load. The FTC is used when greater stacking strength and resistance to bulging are required. Smaller size cartons (14 lb) are also used, especially for overseas markets. Almost all corrugated fiberboard containers are shipped to the packer flat and require hand or machine assembly onsite. (Figure 35A)
Plastic Bags	A newer, low-cost material for consumer-sized packaging. Film bags are clear, allowing for easy inspection of the contents. They readily accept high-quality graphics and are available in a wide range of thicknesses, grades, and gas permeability. Decay is a risk if a low-oxygen and high-moisture environment develops within the bags, which is more likely to occur with extended storage time or if the bags are stacked. Specialized bagging equipment is required. (Figure 35B)
Shrink Wrap	One of the newer trends in packaging is shrink-wrapping of individual roots, which can reduce moisture loss, reduce mechanical damage during shipping, and provide a good surface for stick-on labels. Roots can be shrink-wrapped in a foam tray of two or three. Some consumers prefer individually wrapped roots for microwave cooking. Only healthy roots should be shrink-wrapped, and film that allows for root respiration must be used. Otherwise, disease problems, particularly Fusarium root rots, can develop. (Figures 35C-D)
Net Bags	Net bags bundle roots into convenient consumer-sized packages. Although they cannot offer the modified-atmosphere possibilities of plastic, they are preferred by many consumers, and good air movement limits the chance of disease development. Specialized bagging equipment is required. (Figure 35E)
Bulk Bins	Large double- or triple-wall corrugated pallet bins are used as one-way pallet bins to ship in bulk form to processors and retailers. Container cost per pound of produce is as little as one-fourth that of 40-pound containers, and some bulk containers may be collapsed and reused. (Figure 35F)

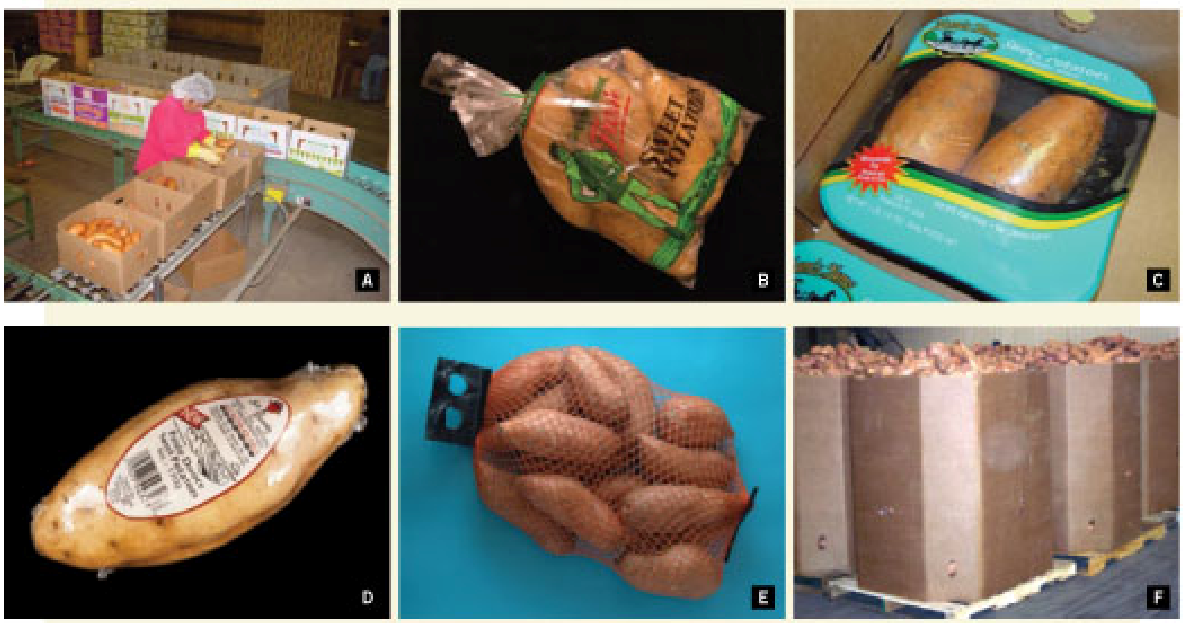

Figure 35. Examples of packaging: corrugated fiberboard (A) (PHOTO BY B. EDMUNDS); plastic bags (B) (PHOTO BY G. HOLMES); tray shrink wrapping (C) (PHOTO BY G. HOLMES); individual root shrink wrapping (D) (PHOTO BY G. HOLMES); net bags (E) (PHOTO BY G. HOLMES); bulk bins (F) (PHOTO BY T. SMITH)

yas, and other tropical fruits that are also held at 55°F (13°C). Also make certain that the refrigeration unit is functioning properly and that no engine exhaust is entering the trailer.

Compatible shipping temperature is the main concern with sweetpotatoes. Many commodities are shipped at temperatures near freezing, which can severely damage sweetpotatoes. Be sure to inform shippers of the temperature requirements (Figure 36). Roots may be chilled if the trailer thermostat is set too low to accommodate other commodities or during long trips in cold weather.

Export-market shipping involves onsite packing of marine containers with pallets or bulk bins (Figure 37). Shipping time by boat to European markets can range from 8 to 14 days, plus the distribution time on either end of the trip. Marine containers for sweetpotatoes are usually not modified-atmosphere environments, but most containers do have temperature control along with vents to provide air exchange. Research on optimal conditions for overseas shipping of sweetpotatoes is minimal. The best source of general information is a publication from the University of California, "Marine Container Transport of Chilled Perishable Produce" (Thompson et al., 2000). This publication states that sweetpotatoes are considered to have low respiration during shipment, so the recommended air-exchange rate is 15 feet^3 per minute (25 meter^3 per hour) for a 40-foot marine container to maintain proper carbon dioxide levels. Container temperature should be maintained at 55°F (13°C). All containers have vents that are left open at a specified setting during transport to ensure fresh air exchange. However, this makes controlling relative humidity difficult. Vent settings vary among container manufacturers, so it is important to set vents by airflow rates in feet^3 per minute or meter^3 per hour, because "percent opening" recommendations may not be reproducible between container manufacturers. Packers should install temperature-recording devices to verify that proper temperatures were maintained during shipping.

MARKET LIFE OF PACKED SWEETPOTATOES:

Market life begins when roots are removed from bulk storage bins. Market life includes washing, packing, and distribution to market, and it concludes at the point of consumer purchase. Temperature and relative humidity often vary greatly at different steps as the roots move from storage to consumer. Market life is maximized when roots are handled gently and temperature and relative humidity are maintained at 55°F (13°C) and 85 percent, respectively. Under these conditions, market life is typically two to three weeks. (Market life should not be confused with storage life, which can be up to 13 months under proper conditions.)

Many factors influence the market life of sweetpotatoes. The cultivar, pre-harvest growing conditions, curing conditions (or lack thereof), storage temperature, relative humidity, atmospheric oxygen/carbon dioxide composition, amount of mechanical injury during packing, wash water sanitation, type of packaging, and air flow and temperature during transport and distribution to market are among the most important factors influencing market life.

Weight loss due to mechanical injuries received during packing is a major cause of quality reduction in the retail market. Weight loss results in shriveled or pithy roots. It can be high, particularly during transit or in supermarket display areas where relative humidity is generally low. For example, recent research with cultivar Beauregard showed weight loss of washed roots in the range of 5 to 10 percent after a four-week period under simulated retail market conditions (about 70°F and 70 percent relative humidity). Consumers prefer sweetpotatoes that have lost less than 5 percent during transit and retail marketing, and that requires proper temperature and humidity control.

It is not possible to make an all-inclusive statement that defines the market life of any commodity. Market life can vary greatly from one lot of product to another for numerous diverse causes. Ultimately, the market subjectively determines the point at which sweetpotato quality becomes unfit for consumption.

Figure 36. Temperature and air exchange controls for shipping container. (PHOTO BY G. HOLMES)

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Figure 37. Marine containers are utilized to transport bulk bins and pallets to overseas export markets. (PHOTO BY G. HOLMES)

Appendix 1.

Guide to Common Postharvest Diseases, Abiotic Damage, and Insects

DISEASES THAT DEVELOP IN STORAGE

Bacterial root rot, caused by *Dickeya dadantii (Pectobacterium (Erwinia) chrysanthemi)*, can occasionally cause heavy losses in storage or after packing. Infection

Figure 38. Bacterial root rot causes a soft, dark rot. (PHOTO BY C. AVERRE)

results in mostly internal, very wet, soft rot that usually occurs during warm humid conditions (Figure 38). Occasionally, bacterial soft rot has developed after sweetpotatoes coming from the field were wetted to help set the skin, or when pallets were wrapped too heavily in plastic for stability during shipping, depriving them of adequate gas exchange. Bacterial soft rot can be internal and without symptom in roots, developing only under the proper conditions. The disease is managed by using planting stocks that are free of disease, avoiding wounding during harvest and handling, using clean water on packing lines, and preventing high carbon dioxide/low oxygen environments with high temperatures.

Black rot infections caused by the fungus *Ceratocystis fimbriata* occur in the field. However, the disease can be spread during harvest from diseased to healthy roots. The presence of even small black rot lesions in the crop during harvest may lead to large losses in storage (Figure 39 A and B). If a small amount of black rot is present at harvest, the lesions will expand in storage. Black rot was once the most important postharvest disease of sweetpotato, but using disease-free seed roots, cutting slips above the soil line, and rotating crops have dramatically reduced its occurrence.

Fusarium surface rot and Fusarium root rot decay caused by *Fusarium* is commonly seen in storage. There are two species of *Fusarium* that cause two distinct symptoms on roots. Fusarium root rot, caused by *Fusarium solani*, is a decay that extends into the flesh of the root. Externally, lesions are dark tan and often have a distinct ring pattern of light and dark brown bands (Figure 40). The rot is firm, dry, and dark brown, with internal cavities often filled with white mycelium of the fungus (Figure 41). Fusarium surface rot, caused by *Fusarium oxysporum*, has surface lesions that do not extend into the flesh. They are generally circular, light to dark brown, firm, and dry. Both diseases can be managed by minimizing injuries during harvesting and handling, harvesting when soil moisture is optimal, curing promptly after harvest, and using cultivars resistant to Fusarium root rot. Fusarium surface and root rots develop slowly and, therefore, are not considered a post-packing disease because there is insufficient time for the diseases to develop between packing and consumption.

Java black rot, caused by the fungus *Lasiodiplodia theobromae*, is occasionally found during storage. This disease is easily identified by its distinct symptoms. Symptoms usually begin at the root end as a firm, moist decay that turns color from pale yellow, to brown, to black (Figure 42).

Figure 39. Black rot caused by *Ceratocystis fimbriata*. (A and B) (PHOTOS BY G. HOLMES)

As the disease progresses, hard black masses called "stroma" break through the surface of the root (Figure 43). With time, these masses will break down to release powdery spores. The fungus enters through a wounded area and can be controlled with good packinghouse sanitation and with prompt curing at the proper temperature and humidity to heal wounds. Java black rot is more common in tropical areas of the world.

Rhizopus soft rot, caused by the fungus *Rhizopus stolonifer*, is the most common disease of stored and packed sweetpotatoes. After the fungus enters the tissues through wounds, it can cause a soft, wet decay of the entire root within three days. Rhizopus soft rot is characterized by white, whiskery fungal growth and prolific dusty black spores on the surface of infected roots (Figure 44). Wet soil and low temperature at harvest cause sweetpotatoes to be especially susceptible, and symptoms appear soon after storage. Rhizopus soft rot is most likely to occur after packing, because infections occur through wounds.

Figure 42. Internal symptoms of Java black rot include a clearly demarcated, firm, dark rot. (PHOTO BY G. HOLMES)

Figure 40. Fusarium surface rot is characterized by sunken, scalloped-edge rings on the root surface. (PHOTO BY G. HOLMES)

Figure 43. External symptoms of Java black rot are hard black "stroma" protruding out of the sweetpotato skin. (PHOTO BY G. HOLMES)

Figure 41. Fusarium root rot shows internal decay with characteristic cavities that may contain white fungal growth. (PHOTO BY G. HOLMES)

Figure 44. Rhizopus soft rot is characterized by a wet, soft rot and whiskery fungal growth covered with powdery black spores. (PHOTO BY G. HOLMES)

Rhizopus soft rot can be managed by properly curing roots to heal wounds incurred during harvest and by avoiding damage on packing lines. Most packers apply fungicide on the packing line. Less susceptible cultivars are available; however, none show complete resistance. For specific fungicide recommendations, refer to the latest edition of the *North Carolina Agricultural Chemicals Manual, Louisiana Plant Disease Management Guide*, or contact your local Extension center for guidelines in your state.

Figure 45. Circular spot is caused by the fungus *Sclerotium rolfsii*. Lesions are unusually circular, and the center of the spot typically cracks. (PHOTO BY G. HOLMES)

Figure 46. Geotrichum sour rot can occur in the field or in storage. It is favored by conditions of low oxygen and high temperature. The disease has a distinctly sour smell. (PHOTO BY G. HOLMES)

DISEASES THAT OCCUR IN THE FIELD AND ARE ALSO SEEN IN STORAGE AND PACKING

Circular spot is caused by the soilborne fungus *Sclerotium rolfsii*, which also causes sclerotial blight in plant beds. The circular, brown, shallow spots (Figure 45) develop on roots just before harvest but do not develop further after harvest unless there is free moisture on the roots during curing. Usually, the roots heal during storage, and the spots begin to peel away from the root.

Geotrichum sour rot begins in the field when flooding occurs and continues to develop in storage. A wet, soft rot develops that has a distinctive fruity-alcohol odor. Tufts of white mycelia develop on the outside of the root (Figure 46). Sour rot can also occur postharvest when roots are exposed to high temperatures and low oxygen environments.

Mottle necrosis is caused by at least two species of the soilborne fungus *Pythium*. Although it occasionally causes significant losses, it is not considered a common disease. External symptoms consist of slightly sunken, brown spots with irregular margins. When affected roots are sliced, a marbled decay is revealed (Figure 47). Avoid cool, wet conditions near harvest, and practice crop rotation.

Soil rot or pox is caused by a soilborne filamentous bacterium (*Streptomyces ipomoea*). Soil rot causes dark corky lesions that are usually indented (Figures 48 and 49). The type of symptom produced depends largely on the timing of infection with respect to root development. Infections occurring prior to root enlargement are more likely to constrict

Figure 47. Mottle necrosis is caused by *Pythium* spp. and produces a distinctive marbled necrosis of the root pith. (PHOTO BY G. HOLMES)

Figure 48. Constrictions can be caused by early season infection with soil rot/pox. (PHOTO BY G. HOLMES)

and disfigure the root, but do not develop further in storage. Growing resistant varieties can greatly reduce the incidence of soil rot or pox. Lowering soil pH through applications of sulfur can reduce disease problems.

Figure 49. Soil rot symptoms also include circular, sunken, dark scabby lesions. (PHOTO BY G. HOLMES)

Figure 50. Russet crack is caused by a virus; slight constrictions and parallel cracking are characteristic symptoms of the disease. (PHOTO BY G. HOLMES)

Russet crack is a disease caused by a strain of the sweet potato feathery mottle virus (SPFMV). In the field, brown bands develop on the skin and extend laterally around parts of the root. Within these brown bands there are usually shallow cracks that run perpendicular to the bands (Figure 50). The symptoms do not change in storage and are often missed until the roots are washed. Russet crack can be managed by a good seed program that utilizes virus-tested, Certified, or Foundation seed.

Scurf, caused by the fungus *Monilochaetes infuscans*, is a common sweetpotato disease that is transmitted primarily by infected planting stock, but it also may persist in soil for 1 to 2 years. Scurf is a disease of the skin (Figure 51). However, roots that are heavily infected with scurf may shrink more rapidly than normal roots. Research has shown that scurf does not spread to other roots during storage. Small, insignificant, infected areas may enlarge, especially in the presence of humidity higher than 90 percent.

Scurf can be managed by using scurf-free planting stock, treating seed with fungicide, avoiding problem fields, rotating land used for plant beds each year and, most importantly, cutting plants above the soil line instead of pulling to reduce the spread from seed plants (Figure 4). Scurf-infected roots should not be used for seed or disposed of in a field where sweetpotatoes will be planted later. USDA Standards (Appendix 2) list scurf covering more than 15 percent of the root surface as a defect.

Slime molds occasionally develop on the surface of sweetpotatoes. Little is known about the conditions that favor slime mold development on storage roots. Although they look superficial (Figure 52), it is difficult to wash slime mold off sweetpotatoes without permanently damaging the skin of the root.

Figure 51. Scurf only affects the root skin; it does not penetrate into the root flesh. USDA standards allow for 15 percent of the root surface to be covered with scurf. (PHOTO BY G. HOLMES)

Figure 52. Slime mold damage to root skin. (PHOTO BY C. CLARK)

ABIOTIC DAMAGE

Chilling Injury is rare, but it can occur if roots are kept in common storage areas during the winter months (or during transit if temperatures are too low). Storage below 55°F (13°C) can result in chilling injury that may not be evident for several weeks. The roots may appear normal, but the flesh will be spongy and watery. When chilled roots are cooked, the central area of the root may remain hard. Chilled roots are often colonized secondarily by *Penicillium* species (Figures 9 through 11).

Growth Cracks are generally caused by uneven growing conditions, usually when drought is followed by heavy rain (Figure 53). These cracks often serve as infection courts for secondary pathogens. Cracking may also be caused by root-knot nematode (Figure 54). Cracks caused by root growth and those caused by nematodes can be distinguished by the presence of nematodes near the surface of the root (Figure 55).

Mutations/Chimeras in flesh color are common in sweetpotatoes (Figures 56 A and B). Sprouts emerging from the mutated flesh color will produce roots of the same flesh color. A good seed program that uses Foundation or Certified seed that has been selected for freedom from mutations can minimize this problem.

Figure 53. Cracking and galling caused by rapid expansion of roots during a period of high soil moisture on cultivar Beauregard. (PHOTO BY G. HOLMES)

Figure 54. Cracking and galling caused by root knot nematode infection on cultivar Beauregard. (PHOTO BY G. HOLMES)

Figure 55. Nematode damage in sweetpotato root. Small dark spots with light centers reveal the locations of female nematode. (PHOTO BY G. HOLMES)

Pithiness usually is a result of poor storage conditions (such as inadequate temperature or humidity control) and is characterized by white spongy flesh that may contain spaces or cavities and by roots that weigh much less than normal (Figure 10).

Skinning is common during rough handling at harvest and packing (Figure 5). Skinning injuries can be healed through the curing process, although the original appearance will never be regained.

INSECTS

In addition to diseases, potential harm from insects in stored sweetpotatoes is of significant economic concern. Among the insects found in sweetpotato storage facilities are fruit flies, soldier flies, corn earworm, beet armyworm, fall armyworm, southern armyworm, and the sweetpotato weevil. Specific recommendations for control of insects using chemicals are found in the *North Carolina Agricultural Chemicals Manual* and the *Louisiana Insect Pest*

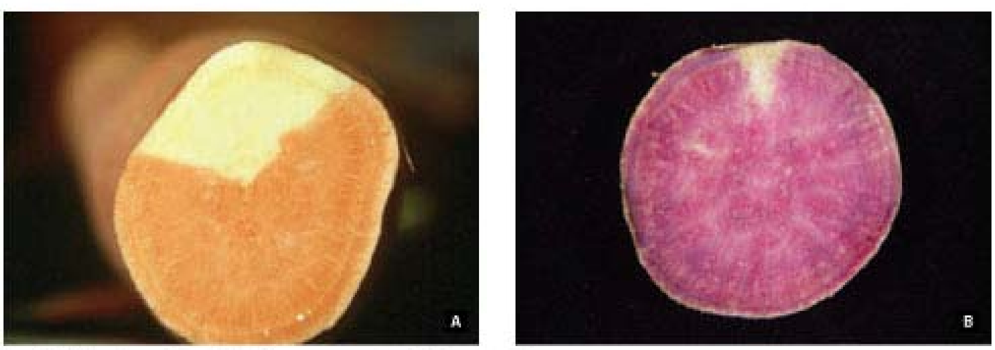

Figure 56. Chimera in orange flesh cultivar (A) (PHOTO BY C. CLARK) and purple flesh cultivar. (B) (PHOTO BY G. HOLMES)

Figure 57. Fruit flies are a common nuisance pest in storage. (PHOTO BY M. WESTER)

Figure 58. Soldier flies are an occasional pest of stored sweetpotatoes. (PHOTO BY B. DREES)

Management Guide, or you can contact your local Extension center for recommendations.

Fruit flies (*Drosophila* spp.) (Figure 57), also known as vinegar flies, pomace flies, sour flies, banana flies, or drunkards, are very common and are usually considered nuisance pests. They quickly breed into tremendous numbers, but they do not directly attack healthy roots. They lay their eggs and reproduce in diseased, soured, or mechanically damaged sweetpotatoes. Their presence in great numbers is a sure indication of a significant decay problem. Conditions that favor fruit flies are high temperatures, coupled with large quantities of sour, diseased, and mechanically bruised sweetpotatoes. Storing only the best quality, undamaged roots and maintaining that quality are the primary means of avoiding fruit flies. An insecticide spray may be justified when extremely high populations are present.

Soldier flies (*Hermetia illucens*) (Figure 58) are most often seen in the form of scavenging, thick-skinned, flattened larvae. Much like fruit flies, they favor warm, wet storage conditions with decaying roots. Other insects such as earworms and armyworms, which feed on the foliage and exposed sweetpotatoes in the field, are at times carried into storage facilities during harvesting operations. There, they continue to feed and cause large holes in roots. Managing

Figure 59. External damage caused by sweetpotato weevil feeding includes small puncture wounds. (PHOTO BY J. MURRAY)

these insects in the field prior to harvest will help avoid introducing worms into storage areas.

Sweetpotato weevil (*Cylas formicarius,Fab.*) (Figures 59 through 61) can be a serious pest of stored sweetpotatoes once it is established. Although they are not considered a problem in the majority of sweetpotato commercial production areas in the U.S., weevils can become a serious pest of stored sweetpotatoes in the South if not properly monitored and managed. Regulatory mandates differ, and growers should become familiar with their local regulations.

Prevention is the key to successful weevil management. Avoid bringing in sweetpotatoes or containers from areas where weevils are known to be a serious problem. Always insist on weevil-free roots when purchasing seed or roots for storage, and inspect shipments upon arrival to verify place of origin and proper tagging. If a threat of weevils exists, sex pheromone traps (Figure 62) that are specific to sweetpotato weevils can be used to monitor plant beds, storage areas, and production fields. If sweetpotato weevils are discovered outside the quarantine area, promptly alert regulatory officials. Certain insecticides are available and labeled for use in the field and in storage facilities. Contact your local Extension agent for more information on the potential risk of and management options available for the sweetpotato weevil in your area.

Figure 60. Internal damage caused by sweetpotato weevil feeding. (PHOTO BY A. HAMMOND)

Figure 61. Adult sweetpotato weevil. (PHOTO BY DIVISION OF PLANT INDUSTRY ARCHIVE, FLORIDA DEPARTMENT OF AGRICULTURE AND CONSUMER SERVICES, BUGWOOD.ORG)

Figure 62. Pheromone traps for sweetpotato weevil are required in infested areas. (PHOTO BY G. HOLMES)

Appendix 2.

U.S. Standards for Grades of Sweetpotatoes

Summarized from the *U.S. standards for grades of sweetpotatoes*. Published by the USDA Agriculture Marketing Service and effective April 21, 2005. For complete information on grade standards, see http://www.ams.usda.gov/

GRADES

U.S. Extra No. 1.
U.S. No. 1.
U.S. No. 1 Petite.
U.S. Commercial.
U.S. No. 2.

TOLERANCES

U.S. Extra No. 1, U.S. No. 1 and U.S. No. 1 Petite grades. 10 percent of the sweetpotatoes in any lot may fail to meet the requirements of these grades, but not more than one-half of this amount, or 5 percent, shall be allowed for sweetpotatoes which are seriously damaged, including therein not more than 2 percent for sweetpotatoes affected by soft rot or wet breakdown.

U.S. Commercial. 25 percent of the sweetpotatoes in any lot may fail to meet the requirements of this grade, but not more than one-fifth of this amount, or 5 percent, shall be allowed for sweetpotatoes which are seriously damaged, including therein not more than 2 percent for sweetpotatoes affected by soft rot or wet breakdown.

U.S. No. 2. 10 percent of the sweetpotatoes in any lot may fail to meet the requirements of this grade, including therein not more than 2 percent for sweetpotatoes affected by soft rot or wet breakdown.

Off-size. 10 percent of the sweetpotatoes in any lot may fail to meet any specified size, but not more than one-half of this amount, or 5 percent, shall be allowed for sweetpotatoes which are below the minimum diameter and minimum length specified.

DEFINITIONS

Similar varietal characteristics: sweetpotatoes have the same character of flesh and practically the same skin color. For example, dry type shall not be mixed with semi-moist or moist type.

Firm: not more than slightly flabby or shriveled.

Smooth: the sweetpotato is free from veining or other defects causing roughness which more than slightly detract from the appearance of the individual sweetpotato or the general appearance of the lot.

Fairly clean: the individual sweetpotato is not caked with dirt and that dirt or other foreign matter does not materially detract from the general appearance of the lot.

Fairly well shaped: the sweetpotatoes are not so curved, crooked, constricted or otherwise misshapen as to materially detract from the appearance of the individual sweetpotato or the general appearance of the lot.

Damage: any defect which materially detracts from the appearance, or the edible or shipping quality of the sweetpotato or which cannot be removed without a loss of more than 5 percent of the total weight of the sweetpotato including peel covering the defective area. Specific defects:

(a) Sprouts over three-fourths inch in length
(b) Growth cracks which detract materially from appearance
(c) Scurf covering more than 15 percent of the surface
(d) Pox (Soil Rot) when detracting from appearance
(e) Wireworm, grass root or similar injury when any hole in a sweetpotato ranging in size from 6 to 8 ounces is more than three-fourths inch long or when the aggregate length of all holes is more than 1¼ inches, or correspondingly shorter or longer holes in smaller or larger sweetpotatoes.

Length: the dimension of the sweetpotato, measured in a straight line between points at or near each end of the sweetpotato where it is at least three-eighths inch in diameter.

Diameter: the greatest dimension of the sweetpotato, measured at right angles to the longitudinal axis.

One type: sweetpotatoes have the same character of flesh, and do not show an extreme range in skin color. For example, dry type shall not be mixed with semi-moist, or moist type, and deep red or purple skin color shall not be mixed with yellow or reddish copper skin color.

Fairly smooth: the sweetpotato is free from veining or other defects causing roughness which detract from appearance.

Serious damage: any defect which seriously detracts from the appearance or edible or shipping quality or which cannot be removed without a loss of more than 10 percent of the total weight of the sweetpotato including peel covering the defective area. The following specific defects shall be considered as serious damage:

(a) Dirt or other foreign matter when the individual sweetpotato is badly caked with dirt, or when seriously detracting from the appearance of the lot;
(b) Growth cracks when unhealed or when seriously detracting from the appearance of the individual sweetpotato or general appearance of the lot;
(c) Pox (Soil Rot) when seriously detracting from the appearance of the individual sweetpotato; and,
(d) Wireworm, grass root or similar injury when any hole in a

TABLE 9. Size requirements for U.S. sweetpotato grades

Grade	Length (in.)		Diameter (in.)		Weight (oz.)
	Min.	Max.	Min.	Max.	Max.
U.S. Extra No.1	3	9	1¾	3¼	18
U.S. No. 1 & US Commercial	3	9	1¾	3½	20
U.S. No. 1 Petite	3	7	1½	2¼	-
U.S. No. 2	1½	-	-	-	36

TABLE 10. Appearance requirements for U.S. sweetpotato grades

U.S. Extra No. 1	US No.1 U.S. No. 1 Petite	U.S. Commercial	U.S. No. 2
Firm	Firm	Firm	Firm
Smooth	Fairly smooth	Fairly smooth	No serious damage
Fairly clean	Fairly clean	Fairly clean	Not dirty
Fairly well shaped	Fairly well shaped	Fairly well shaped	No shape requirement
Similar varietal characteristics	One type	One type	One type
Free of damage*	Free of damage*	Free of serious damage*	Free of serious damage*
Free of chilling injury, internal breakdown and dry rot	Free of chilling injury, internal breakdown and dry rot	Free of chilling injury, internal breakdown and dry rot	Free of chilling injury, internal breakdown and dry rot
<2% soft rot	<2% soft rot	<2% soft rot	<2% soft rot

*See definitions above for description of damage and serious damage

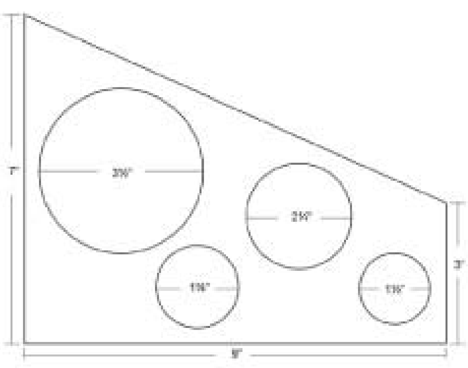

Figure 63. A grading board can be used in the field and on the packing line to manually grade roots. (ILLUSTRATION BY B. EDMONDS)

sweetpotato ranging in size from 6 to 8 ounces, is more than 1¼ inches long, or when the aggregate length of all holes is more than 2 inches, or correspondingly shorter or longer holes in smaller or larger sweetpotatoes.

A grading board (Figure 63) can be used by growers, graders and packers to determine size classification. A grading board can be made from plywood, metal, Masonite, or plastic. Unless otherwise specified, sweetpotatoes that go through the large hole (left) but not through the small hole (right) and are between three and nine inches in length meet the requirements for U.S. No. 1 size. Additional holes can be made for sizing other grades.

Appendix 3.

Construction Guidelines for Negative Horizontal Ventilation (NHV) Curing and Storage Facilities

Revised from *The Postharvest Handling of Sweetpotatoes: with construction guidelines for negative horizontal ventilation curing and storage facilities.* M.D. Boyette, E.A. Estes, A.R. Rubin, and K.A. Sorenson. 1997. North Carolina Extension Service publication AG-413-10-B

In the 1970s, the Southeast sweetpotato industry began to evolve as a reliable source of good-quality sweetpotatoes, not only in the fall and early winter, but essentially year-round. A growing concern about the quality of stored sweetpotatoes, combined with a move toward larger and more mechanized operations, eventually prompted a re-examination of then-current curing and storage facility design. In Europe, a design known as the "letter-box," or negative horizontal ventilation (NHV) system, had long been employed for ventilation of (Irish) potato storage facilities. During the 1980s, a variation of this design produced excellent results in California and other regions for forced-air cooling of fruit and vegetables in pallet bins.

In the NHV system, the ventilation air is generally pulled horizontally past the pallet bins by a slight negative pressure. The negative pressure is created by fans mounted internally along the top of a plenum wall on one end of the room (Figure 12). The NHV system mixes the air, which results in little internal variation in temperature or humidity throughout the room. Further, because the air is in motion and passing through the mass of sweetpotatoes (no root is more than one-half the depth of a pallet bin from a moving stream of air), there is opportunity for heat transfer. Good heat transfer is important for warming the sweetpotatoes at the beginning of the curing cycle, or cooling at the end, and for the removal of heat generated by respiration throughout the storage period.

A sweetpotato curing and storage facility is an investment in quality maintenance. In general, the longer the storage time, the more sophisticated the facility and hence, the more expensive. Postharvest facilities, unlike many other types of large capital expenditures (such as tractors and harvesters), are frequently subject to alterations and additions. It is a major mistake to assume that any building design is "final." Economic conditions, marketing opportunities, and many other forces tend to alter the requirements of these structures. Very few of these buildings remain as they were built for more than a few years. A facility with excessive and unused capacity makes little economic sense. However, planning for future expansion or alteration should begin with site selection. After a facility is built, all future expansions must necessarily "work around" that facility. A great many problems can be avoided with proper planning.

The following important points should be seriously considered during the planning process:

Function. The first step in planning is to determine the primary function of the facility. Will the facility be used only for curing and storing sweetpotatoes? Do immediate or long-term plans include provisions for a packing line and possible cold storage? Will the facility be used for other types of produce or for other purposes (for example, equipment storage or storage of other crops or supplies) during the off-season? Will activities at the facility be mostly seasonal, or will there be workers at the facility year-round? A useful and efficient facility can be built only when all the needs and functions have been thoroughly explored.

Location. The chain from sweetpotato field to the consumer's table is essentially an exercise in material handling. Visualizing the movement of sweetpotatoes to the facility, through the facility, and away from the facility as a flow of material can significantly simplify the planning process. Land is expensive. Situating an 8,000-square-foot sweetpotato facility in the middle of a 10-acre field may seem a waste of valuable land. However, there are hundreds of postharvest facilities on sites that effectively eliminate any future expansion, even though the facility was originally conveniently located. There are no good guidelines to follow in projecting what future requirements might be, although it is often recommended that a site should have room for a facility to be doubled in size twice. The outlines of a generous expansion program should be included on the original site plan.

As you begin planning, it is a good idea to become familiar with any zoning regulations, local ordinances, or land-use plans that are applicable to the site. You should also become familiar with any laws or regulations pertaining to construction, electrical systems, worker health or safety, the proper use and storage of pesticides, and the proper handling and storage of food products. Although building contractors should be familiar with the laws governing construction, do not assume they are familiar with laws governing the use of the facility.

Before any construction activity, the owners or operators of a sweetpotato facility are urged to complete a comprehensive site evaluation to ensure that wetlands or other sensitive areas will not be affected by the proposed activity. Most county planning departments maintain a comprehensive list of rules and regulations that may impact small businesses and industries. Early contact with regulatory agencies is recommended to ensure that the construction and use of the facility are in compliance with all applicable rules and regulations and that all necessary permits are acquired.

A level, elevated site with good natural drainage is ideal. Standing water is not only a nuisance, but it contributes to the early failure of floors, foundation walls, and column footings. Further, pumping water from loading docks—especially pumping wastewater from packing lines—can be expensive. Avoid sites too near property lines, creeks (and designated wetlands), and railroad, highway, or power rights-of-way. It is also prudent to avoid residential areas whenever possible. Although highway accessibility is essential both for the movement of sweetpotatoes and for those working in the facility, try to maintain a reasonable setback. Allow for adequate parking and truck turnaround space, provide room for future expansion, and avoid potential problems should the highway be altered or widened.

Power. All except the smallest sweetpotato curing and storage facilities should have access to three-phase power. Access may be problematic in some rural areas, but the amount of power required for fans, pumps, and refrigeration systems makes access to three-phase essential in most cases. Although the cost of three-phase power may be considerably less than single phase, connection fees may be quite high. However, the cost of running three-phase equipment may be considerably less than single phase. For example, a five-horsepower, three-phase electric motor may cost about the same as a one-horsepower, single-phase electric motor. Some electrical equipment, such as refrigeration systems with a capacity greater than 10 tons, may require three-phase power. Power stand-by charges or minimum monthly charges may be levied if power is not disconnected in the off-season, so check details with your utility company.

Water. Some water is required for all sweetpotato curing and storage facilities. For facilities intended for curing and storage only, 8 to 12 gallons per minute may be adequate for humidifiers, drinking, bathrooms, and miscellaneous cleaning. However, for facilities with packing lines, the water requirements may range from 1,000 gallons per hour for a small line to more than 3,000 gallons per hour for a large line. If well water is to be the source, follow local permit requirements. Back-flow protection should be incorporated into any well's construction design.

Waste disposal. For a curing and storage facility that may include a packing line, you should closely examine proper waste disposal options. All such facilities must have means for proper management and disposal of both domestic and industrial process waste and may also require one or more regulatory permits, depending on state regulations.

Potential sites that are otherwise suitable may be rejected because they do not provide for the proper disposal of wastewater. Land application of the wastewater, through spray irrigation or other means, should be explored first. The guidelines for this option may require an assessment by a qualified irrigation engineer, depending on the state. This is definitely the best option for most operations. A second alternative is to discharge to a municipal wastewater treatment system, which may have industrial pretreatment requirements of its own.

A final option is to discharge wastewater into the surface waters (stream, canal, drainage ditch, road ditch, and so on). If you are classified as an industrial operation, (you pack any sweetpotatoes other than your own), you may also be required to obtain a wastewater discharge permit. You should try to avoid this step if at all possible. These permits are issued only after all options for land application or reuse are evaluated. Permits to discharge to surface waters are issued only after the surface water and flow regime has been modeled and discharge limits are established. This is a long and often costly process, resulting in only a temporary permit that is subject to review.

In addition to permits for wastewater management, additional permits may be required for managing the solid waste. The solid waste generated in a sweetpotato packing facility, such as culls, mud, sand, and plastic and paper packaging materials, must be disposed of in a permitted landfill or through some permitted on-site composting facility. The quality of the composted materials must be monitored and can be determined through testing by state regulatory agencies for a small fee. Detailed information on composting methods and equipment may be obtained from your county Cooperative Extension center. Land application or livestock feeding of cull potatoes may also be an option.

Capacity. Many of the details of a sweetpotato curing and storage facility are ultimately determined by the required capacity. The capacity requirements are not always so simple as the sum of your anticipated production, plus the amount you might be willing to store for others. The practices of segregating the roots from different growers, from different fields, of different grades or different varieties, and arranging them for easy access, can all have a significant effect on the working capacity of an individual facility. It makes no economic sense to build more capacity than can be efficiently utilized. A measure of excess capacity may be a wise investment when it will be needed to accommodate higher than normal yields or to provide adequate space to store sweetpotatoes from other sources. Remember that the cost per square foot decreases and energy efficiency increases with increasing facility size.

Curing, unlike storage, is a process that involves a definite period of time. Curing for too short or too long a time can have negative effects on the quality of the roots. For this reason, the size of the individual rooms in an NHV facility is customarily limited to no more than two days' harvest. Two days' harvest for some growers may be as few as 5,000 bushels, while for others it may be as many as 30,000 bushels. The typical capacity of an individual room in an NHV facility is about 15,000 bushels. Larger rooms may make slightly more efficient use of space than smaller rooms, but they can result in undercured or overcured roots if not filled on a timely basis. Smaller rooms, however, are more quickly emptied and taken out of service.

Although there have been some notable efforts in the handling and storage of sweetpotatoes in bulk, almost 100 percent of the domestic sweetpotato crop is still harvested into, cured, and stored in pallet bins. Although there are published standards for pallet bins (ASAE 337.1, American Plywood Association and the National Wooden Pallet and Container Association), the construction and dimensions of the bins have evolved through voluntary agreements between the manufacturers and the sweetpotato industry. In the Southeast, most pallet bins built since about 1985 for sweetpotatoes have generally measured 42 inches wide, 47 inches deep (in the direction of the fork slots), and 35 inches high. The level, full capacity of these bins is slightly more than 20 bushels. In practice, however, to prevent crushing and skinning the roots, the bins are not filled to capacity, but are assumed to hold 18 bushels. The gross weight of a full bin at harvest is approximately 1,250 pounds. In recent years, some growers have moved to double-pallet bins for increased efficiency. These double bins (84 inches wide, 47 deep, and 35 inches high) are designed to exactly replace two single bins but require heavier forklifts and specialized bin rotation equipment.

Pallet bins are designed to be stacked one on top of the other to make efficient use of floor space. It is customary to stack bins at least six high ($17^1/_2$ feet). This allows only $2^1/_2$ feet of head space around the walls in buildings with 20-foot eave height. This should be considered a minimum in NHV facilities. Ample head space is necessary above the stack for proper air movement. Some recently built facilities have 22-, 24-, or even 30-foot eave heights. A 30-foot eave height allows pallet bins to be stacked eight high (23.3 feet). All stacked pallet bins should be perfectly aligned and in good condition. The collapse of one lower pallet bin can cause a stack—or even an entire row—to fall over, with catastrophic results.

As mentioned, the total capacity of a sweetpotato curing and storage facility depends on production plus some prudent excess, whereas the capacity of individual rooms is usually limited to two days' harvest. Most sweetpotato curing and storage facilities consist of several individual rooms. Use the following formulas and guidelines to determine the actual dimensions of these rooms:

> C = (1.2)(L)(W)(N) *Where*:
> C = room capacity in bushels, normally limited to two days' harvest
> L = length of the room in feet
> W = width of room in feet
> N = number of bins in stack, (for example, if the bins are stacked six high, N = 6)

The length of the room (dimension parallel to the direction of air flow) is normally limited to 100 feet because of the difficulty of the fans to consistently move the air greater distances. Although there are no such limits on the width of the room, good planning suggests the selection of room widths that utilize standard building components (beams, girders, and bar joists) and limit the length of unsupported roof spans. It is also a good idea to select widths that match well with the combined width of the pallet bins, plus about two feet to take care of gaps between bins and clearance along both walls. Support columns in the middle of a room are a major inconvenience, a possible safety hazard, and should be avoided when possible.

> Example: A room eight bins wide would require a room width of: W = (8)(42) + 24 = 360 inches = 30 feet. Assuming a room capacity of 12,000 bushels with pallet bins stacked six high, the formula above would yield a calculated length of: 12,000 = (1.2)(L)(30)(6) L= 55.6 feet.

When the width of the plenum is added, the total length of the room approaches 60 feet. Therefore, the capacity of a single room for an NHV facility with inside dimensions of 30 feet wide by 60 feet long, with bins stacked six high, is approximately 12,000 bushels. Table 11 provides estimated capacities for rooms of various dimensions.

If the pallet bins are carefully stacked near the door, almost all the floor space inside the room may be used. Often the pallets in the last row or pair of rows must be turned sideways (the forklift slots are perpendicular to the flow of air in the room) to allow the forklift maneuvering room. This arrangement will present no air movement problems, provided a free space of 6 inches to 1 foot is maintained around these bins.

Rarely will a curing and storage room be built without some type of paved (and often covered) staging area for unloading and loading trucks. Carefully consider this aspect of the facility design. Such areas are seldom considered in initial designs but often become a central alleyway of an expanded facility. This area is important to the overall functioning of the facility because convenient access to each room from a central location is essential for ease of material handling. Access aisles and alleyways should be at least 16 feet wide to allow for safe operation of loaded forklifts. When loading docks are part of the design, they should be conveniently located to keep the trips short from truck to storage.

CONSTRUCTION POINTS AND EQUIPMENT SELECTION

Building type. Many types of building construction have proved satisfactory for sweetpotato curing and storage facilities. Insulated concrete-block, curtain-wall buildings with bar joist roof supports were once popular with growers. Because of the labor costs, block construction has been almost replaced by engineered post-frame buildings or all steel buildings of various designs. These modern buildings are durable, functional, economical, and can be custom designed and constructed in a fraction of the time it took to build the older masonry buildings.

Foundation and floor. Although the cost of the foundation is relatively small, the foundation directly or indirectly affects the performance of all other parts of the building. The foundation distributes the weight of the building and its contents over an area sufficient to prevent excessive and uneven settling. A well-drained solid grade is essential to an acceptable foundation.

All sweetpotato curing and storage facilities are constructed on a slab floor of at least 4 inches of wire-mesh-reinforced concrete over a well-compacted grade. The floor should be capable of supporting at least three times the rated capacity of the forklift. Five to 8 inches of reinforced concrete may be necessary where loads are unusually heavy, such as around loading docks. The floor should be as smooth and level as possible. Even a slight unevenness of $^{1}/_{4}$ inch between the two front wheels of the forklift may result in a 3-inch side movement of the pallet bin 16 feet off the floor (Figure 64). Because the recommended sweetpotato storage temperature is near the deep soil temperature in most growing areas of the U.S., under-floor insulation is not necessary. It is wise, however, to include a vapor barrier under the slab.

Insulation. Thermal energy flows naturally from warm objects to cold ones. All material, even good heat conductors like metals, offers some resistance to the flow of heat. Insulation, however, is any material that offers high resistance to the flow of energy. Hundreds of different

Figure 64. Extended forklift. PHOTO BY T. SMITH

materials have been used at one time or another for thermal insulation. The characteristics of the insulation materials differ considerably. Suitability for the particular application, as well as cost, should be the deciding factors in choosing a material. Thermal resistance (R-factor) should be considered in addition to durability and the labor required to install the material. Some common insulation materials such as fiberglass bats are not recommended for sweetpotato curing and storage facilities because they perform poorly in a high-humidity environment and often harbor rodents and birds.

A measure of an insulation's resistance to the movement of heat is its R-value. The R (for resistance) number is always associated with a thickness: the higher the R-value, the higher the resistance and the better the insulating properties of the material. The R-value can be given in terms of a 1-inch-thick layer or in terms of the total thickness of the material. The R-values of some common building materials are shown in Table 12.

The most popular insulation material now used in new sweetpotato curing and storage facilities is sprayed-on expanded polyurethane foam. Properly applied, this material has an R-factor of approximately 7 per inch, although this value may decrease somewhat with age. It is durable, moisture resistant, and effectively seals cracks and small openings. Its most important characteristic, however, is that it may be applied very rapidly with comparatively little labor. But this material is extremely flammable immediately after application and gives off a toxic smoke when burned. Some local fire codes or insurance companies may require a fire-resistant coating on this material. Fire-protective coating may provide some moisture resistance that is not permanent in urethane, causing the foam's R-factor to decline with age.

Rigid boards of foil or plastic-backed polyisocyranuate foam have been occasionally used for insulating sweetpotato facilities. This material varies in thicknesses (1/2 inch to 3 inches) and in size (4 by 8 feet to as large as 8 by 30 feet). Certain formulations of this material may have R-factors as high as 8 per inch. In the past, similar materials have delaminated and otherwise performed poorly in the high humidity of a sweetpotato facility. This material also requires considerable installation labor. The main objection to this material in an NHV facility in the past was the difficulty in sealing the joints between boards and at roof and floor level. Because NHV facilities operate at slightly reduced or elevated air pressures, failure to adequately seal all openings to the outside can substantially reduce the performance of the system. Newer materials, joint sealing methods, and installation procedures have all but eliminated many of these objections.

Both sprayed-on expanded polyurethane and polyisocyranuate board materials are made of closed cell foams. Closed cell foams act as vapor barriers by retarding the movement of moisture out of the building. A good vapor barrier is desirable to maintain the humidity inside the facility, thereby preventing excessive evaporation and weight loss of the sweetpotatoes. Under high-humidity conditions, sufficient insulation will help prevent moisture from condensing on the walls and roof. When the relative humidity inside the building approaches saturation, moisture will begin to condense on any surface that is below the temperature of the air. Condensation is more likely to occur in the top of the building, is most prevalent at night, and indicates insufficient insulation rather than excessive humidity.

In the sweetpotato growing areas in the Southeast, the total R-factor should be a minimum of 12 for walls and a minimum of 16 for roofs. Roofs require greater insulation because their surfaces are more directly exposed to sunlight during the day and radiation cooling at night.

Doors. The door is another important part of the sweetpotato facility. The larger the door, the better the access to the room and the easier pallet bins may be moved in and out. However, well-designed doors can be expensive. Their price is roughly based on their total area, not width. For example, a 16-foot wide by 16-foot tall sliding or garage door may cost up to four times as much as an 8-foot door. Although small doors are less expensive, few sweetpotato facilities are built with doorways less than 12 feet wide. Doorways should exceed the height of a loaded forklift (about 10 to 11 feet). Improperly designed or maintained doors can waste large quantities of energy. Doors should have as much insulation as the walls and should always provide a good air seal when closed.

Plastic strip curtains are effective in reducing the energy loss when large doors must remain open for long periods. Because the doors of sweetpotato rooms are usually opened only when filling and unfilling, plastic strip curtains are probably not a good investment. Small access doors are a good investment, however, because they allow for inspection of the room and its contents without the bother and energy loss of opening the large access door (Figure 65).

Heating system. Those familiar with the heating requirements of the old trench floor system of curing are sometimes surprised at how much lower the heating requirement is for the NHV system. In general, the heating systems selected for the trench floor facilities were based not on the required heat capacity, but on the fan or air-moving capacity of the heating unit. It is not unusual to see a 12,000-bushel, trench-floor curing room with a heating system capacity of 1 million Btu per hour or more. The actual heating requirement for an NHV room of the same capacity with the recommended minimum insulation is about 300,000 Btu per hour. Because in the NHV system, the fans that move the air about the room are separate from the heating system, the heating system may be rightly based on the heat requirement and not the fan capacity.

Sweetpotatoes delivered to the curing and storage facility usually arrive at a temperature near that of the outside air. Early in the harvest season, this may be near 85°F (30°C), the recommended curing temperature. On cold days late in the harvest season, however, the arriving roots may be significantly cooler. The amount of heat required to warm the sweetpotatoes to the recommended curing temperature depends on their pulp temperature at arrival, the quantity and rate delivered, and the rate of warm up. Generally, sufficient heat should be provided in the curing room to raise the temperature to 85°F (30°C) within *48 hours*. This is an important point. In the past, heating systems were designed to raise the temperature of the roots as much as 40°F in 24 hours. This rate of heat input is excessive for two reasons. First, it often causes drying and other physiological problems associated with high temperatures in localized areas near the heater, even in facilities equipped with NHV systems. The fans simply cannot move the heated air away from the heater fast enough to prevent localized overheating. Second, there is some evidence that abrupt changes in temperature (from cool to warm or vice-versa) may negatively affect sweetpotato metabolism, decreasing quality and shelf life.

Excessively high curing temperatures contribute to excessive weight loss, sprouting, and other possible damage. Although 85°F (30°C) is the recommended curing temperature, it is prudent to stop or slow the input of heat well before that temperature is reached to prevent overshooting the target temperature. Excursions to 90°F (32°C) or even 100°F (38°C) are common problems that occur because of the production of respiration heat at high temperatures. For this reason, it is recommended that the curing thermostat be set no higher than 80°F to allow the pulp temperature to "coast" to 85°F (30°C).

Heating system load calculations are based primarily on two factors. The major factor is the heat required to raise the temperature of the sweetpotatoes from the ambient

Figure 65. Small access doors to storage rooms limit excessive temperature fluctuations that occur when checking root quality or room conditions. (PHOTO BY G. HOLMES)

Operating experience with well-constructed NHV facilities in eastern North Carolina has shown that heating systems sized at 25 Btu per hour per bushel of capacity are adequate.

temperature to 85°F (30°C) at the beginning of the curing cycle. In a properly insulated building, this typically represents 90 to 95 percent of the total load. The rest of the load is composed of heat lost by conduction through the walls and heat lost with ventilation air.

The room from the previous example (30 feet wide by 60 feet long, 12,000 bushel capacity), insulated to R-12 in the walls and R-16 in the roof, would require a heater output of approximately 300,000 Btu per hour. About 94 percent of this total (282,000 Btu per hour) is needed to raise the sweetpotatoes to curing temperature in 48 hours. Only 6 percent of that capacity (18,000 Btu per hour) is needed to offset the conduction and ventilation losses on cold days.

As this example shows, in a properly insulated and operated curing facility, most of the heat load is used to raise the temperature of the sweetpotatoes. Only a small percentage of the heat load is used to offset infiltration losses. Even in very cold weather, heaters are seldom operated because heat from respiration of the sweetpotatoes generally maintains the correct storage temperature. For this reason, it is possible to accurately estimate the required heating system output based solely on the capacity of the facility, provided it is adequately insulated and properly operated. Operating experience with well-constructed NHV facilities in eastern North Carolina has shown that heating systems sized at *25 Btu per hour per bushel of capacity* are adequate. Curing and storage facilities with as little as 10 Btu per hour per bushel have been successfully operated, but in cool weather may take four days or more to raise the curing temperature to 85°F (30°C).

Many different types of oil or gas heaters have been used successfully in sweetpotato curing and storage facilities. Most recently built NHV facilities have used unvented LP or natural gas heaters of the type used in animal confinement buildings or some greenhouses. These unvented gas heaters are simple, relatively inexpensive, and economical to operate. No matter what type of heater is used, it is important that the combustion air for the heater not come from inside the room. Unvented gas heaters in particular can quickly deplete the oxygen inside the room, which results in poor combustion, the production of carbon monoxide, and a potentially deadly situation. Ethylene is a by-product of heaters and can negatively affect sweetpotato quality. Heaters should always be mounted outside the room in some convenient location. Above and to the side of the roll-up or sliding door at the end of the room opposite the plenum wall has proven satisfactory. A duct can be put through the wall from the heater so the hot air enters the room above the stack of pallet bins. The heaters can also be located at the opposite end of the building and ducted into the plenum. Ideally, the thermostat used to control the heater should be located away from the heater in a position that has good air movement and allows easy access (but not directly on an exterior wall if possible).

Refrigeration system. The refrigeration system removes excess heat from the sweetpotato facility. It is possible to store sweetpotatoes for extended periods in both conventional and NHV facilities during cool weather without refrigeration. However, refrigeration allows the timely removal of heat at the end of the curing cycle, which eliminates excessive sprouting and weight loss. Additionally, refrigeration allows for much more precise control of the temperature during storage in warm weather and is essential for successful sweetpotato storage during late spring and summer. In late-season storage situations, the cost of refrigeration generally pays for itself in two years or less by reduced weight loss and increased quality maintenance.

Heat can be thought of as a form of energy that always flows "downhill" from warm objects to cool objects. For example, heat will flow from a warm sweetpotato to the cool surrounding air. A refrigeration system is functionally like a pump that pumps heat "uphill" from cool to warm objects. With a refrigeration system, it is possible to remove heat from a sweetpotato storage room at 65°F (18°C) to the outside air, which may be at 90°F (32°C).

A refrigeration system consists of three major parts: a motor/refrigerant compressor set, condenser coils, and evaporator (cooling) coils. These parts are connected by piping to form a closed loop. Sealed inside the piping is a liquid or vapor refrigerant. The motor/compressor acts as a pump that circulates the refrigerant through the system. Both the compressor and condenser coils are heat transfer devices and have fans to help move heat from the coils to or from the surrounding air. The evaporator coils are always located inside the room and are designed to transfer heat from the air to the refrigerant. The condenser coils are always located outside the refrigerated room and are designed to transfer heat from the refrigerant to the surrounding air. The refrigeration system is controlled by a cooling thermostat. Like the heating thermostat, the cooling thermostat should be conveniently located, but not be directly in the air stream from the cooling coils or on an exterior wall.

The cooling coils of the refrigeration system must be cooler than the air inside the room if the air is to be cooled. The larger the temperature difference, the greater the rate of heat transfer and the smaller and less expensive the cooling coils for a given capacity. However, the colder the coil surface, the more water vapor from the air will condense on the coils. As water condenses on the coils, it gives up heat at the rate of approximately 1,000 Btu per pint. The cooling energy used to remove this latent heat is wasted because it contributes nothing to cooling the room. In addition to wasting refrigeration capacity and electrical power, excessive condensation on the cooling coils should be minimized because it reduces the relative humidity of the room.

To minimize condensation and maintain the optimum curing and storage humidity inside the facility, it is good practice to select a cooling coil that minimizes the temperature difference between the air and coil surfaces by selecting a larger coil. The temperature difference between the air and the coil surfaces (known in the industry as "delta T") should be limited to 12 degrees or less to help maintain a relative humidity of 85 percent. Unfortunately, not all refrigeration contractors are aware of the special humidity requirements of sweetpotato storage facilities. In selecting a cooling coil, be sure to specify a 12-degree maximum delta T. The cooling coils of a refrigeration system are normally equipped with fans that blow or pull air past the heat transfer surfaces. It is advantageous to position the cooling coils inside the room in a way that allows the fans to move air in the same direction as the NHV fans in the plenum wall as shown in Figure 12. Allowing the cooling coils fans to move air across the room perpendicular to the direction of air from the NHV system, or even worse, opposite of that from the NHV fans, will disrupt the air flow patterns, and the result is poor performance of the NHV system.

Similar to the heating system, the refrigeration load calculations are based on two factors. The main factor is the refrigeration capacity required to remove the heat from the roots at the end of the curing cycle. In determining this part of the load, timely removal of heat to reduce weight loss must be balanced with the cost of the system. The longer the time allowed to reduce the temperature from 85°F (30°C) to 58°F (15°C), the smaller the refrigeration load and hence, the smaller and less costly the system. Experience has shown that a cool-down period of 96 hours (four days) strikes a good balance between quality maintenance and cost. In a well-insulated and operated NHV facility, this cool-down generally represents approximately 90 percent of the total required refrigeration load. Similar to heating, the other factor representing the remaining 10 percent is the refrigeration capacity required to overcome the conduction losses through the walls and roof and the ventilation losses.

Using the previous example—a 30-by-60-foot, 12,000-bushel capacity room—the facility would require a refrigeration capacity of approximately 185,000 Btu per hour (15.4 refrigeration tons). More than 90 percent of this amount is needed to lower the temperature at the end of curing. The other 10 percent is needed to offset the heat gained through conduction and ventilation. As with the heating system calculations, it is possible to accurately estimate the refrigeration system capacity required based solely on the capacity of the facility, provided it is adequately insulated and properly operated. Again, operating experience with well-constructed NHV facilities has shown that about 1.3 tons of refrigeration per 1,000 bushels of capacity is adequate.

Again, operating experience with well-constructed NHV facilities has shown that about 1.3 tons of refrigeration per 1,000 bushels of capacity is adequate.

Humidification equipment. For successful curing and storage of sweetpotatoes, maintaining the proper humidity should be considered almost as important as maintaining the proper temperature. In NHV facilities that are cooled with outside air only, low humidity and the resulting weight loss can be a serious problem without humidity control. Some water vapor is continually given up by sweetpotatoes, either by evaporation or by respiration. Under normal curing and storage conditions, however, this is not enough to maintain the humidity at 85 percent. To maintain optimum humidity, some provisions must be made to add additional water to the air. Traditional recommendations to wet the walls or floors are ineffective. The water must be evaporated directly into the air stream to raise the humidity quickly and uniformly throughout the room. A well-designed humidifier is the only way to efficiently accomplish this.

Many good humidifiers are available that are suitable for a sweetpotato curing and storage facility. Most consist of an electrically driven, high-speed fan and atomizer that produces a fine mist. Ideally, this mist is quickly evaporated, picked up by the circulating air, and distributed throughout the room. Properly adjusted, humidifiers in a sweetpotato facility will not moisten the floor, the sweetpotatoes, or any other surface. The purpose of humidification is to fill the sweetpotato facility with water vapor, not a fog of water droplets. For this reason, those humidifiers designed primarily for greenhouses should be avoided, because they often produce relatively large droplets that settle out of the air stream before they evaporate.

The selected humidifier should have a rated capacity of approximately one gallon per hour per 5,000 bushels of facility storage capacity. The rated capacity of the humidifier is indicative of its performance in low humidity. As the humidity in the facility increases to ideal levels, some of the water droplets may not completely evaporate and drip onto the floor or other surfaces. Additionally, water sources often contain lime or other chemicals that form deposits on nozzles, fan blades, and other parts of the humidifier. The deposits can adversely affect the performance of the unit and should be removed during periodic maintenance. For this reason, humidifiers should be positioned conveniently for ease of servicing. Because the evaporation of moisture cools the air, it is advisable to mount the humidifier near the heat duct to help warm the air cooled by evaporation and further accelerate the evaporation of water droplets.

...the total fan capacity of the NHV facility must equal approximately 2 cfm per bushel based on a fan static pressure differential of 0.10 inches of water.

What cannot be measured, cannot be controlled. Humidity can be measured by hand using an inexpensive device called a sling psychrometer, using wet bulb and a dry bulb air temperature with a constant air speed passing over the thermometer (Figure 66). Other devices also can be incorporated into automated systems. They measure humidity electronically or by the shrinking or swelling of specially treated materials. A humidistat, which is an adjustable humidity sensor that activates a switch, should always be used to control the humidifier. Manual control of the humidifier by a simple on/off switch will invariably result in poor humidity maintenance. The humidistat should be properly positioned for best results. It should not be located too near the humidifier nor directly in the air stream from the cooling coils or heater.

Figure 66. A sling psychrometer is used to manually measure humidity. (PHOTO BY G. HOLMES)

Ventilation equipment. The fans mounted in the plenum wall are the essential elements of the NHV system. Along with the dampers and louvers, the fans regulate the movement of air inside the facility. Guidelines for the proper selection of this equipment are based on research and practical field experience in a variety of NHV facilities. The horizontal movement of air not only promotes uniform conditions of temperature and humidity throughout the mass of sweetpotatoes, but more important, it provides a means for heat transfer by forced convection. This forced convection allows the temperature of the sweetpotatoes to be raised uniformly at the beginning of curing and lowered at the end. It also allows for the timely removal of respiration heat and the maintenance of uniform conditions of temperature and humidity throughout the room.

Experimental data for heat transfer between the sweetpotatoes and the air forms the basis on which the required fan capacity is determined. If each of the pallet bins were exactly the same size and fitted perfectly together so that air leakage between bins was eliminated, approximately one cubic foot per minute (cfm) per bushel would be more than enough air to effect good heat transfer. Experimental evidence has shown, however, that about half the air passing through the fans leaks into the plenum through gaps between the pallet bins. Therefore, to yield satisfactory results, the total fan capacity of the NHV facility must equal approximately 2 cfm per bushel based on a fan static pressure differential of 0.10 inches of water. Fan manufacturers normally supply charts giving volume flow rate as a function of static pressure.

Correct fan selection is essential to the proper operation of an NHV facility. Industrial ventilation axial flow fans similar to those shown in Figure 13 are offered in many different combinations of blade diameter, motor horsepower, and fan capacity. In general, where two fans of different blade diameter and horsepower have similar capacity, the one with the larger blade diameter is more energy efficient. Although it is possible that only one fan could provide sufficient capacity, experience has shown that multiple fans spaced 10 to 12 feet apart along the plenum wall will distribute air more uniformly. All the fans in a room must be operated simultaneously. If some fans are allowed to operate while others are switched off or otherwise inoperable, air will be drawn backwards into the plenum through the nonoperating fans. This will significantly reduce air movement through the sweetpotatoes, waste energy, and compromise environmental control. Always promptly repair inoperable fans.

When the fans are used to simply circulate the air inside the room, the motorized dampers across the plenum from the fans remain closed. When outside air is required, the dampers are opened. When correctly sized, the total damper area should equal approximately two-thirds of the total fan area. The total area of the gravity shutters at the end of the room opposite the plenum should equal the total area of the motorized dampers.

Using the example facility of a 30-by 60-foot, 12,000-bushel capacity room, the total required fan capacity would be approximately 2(12,000) = 24,000 cfm. Assuming that three fans spaced approximately 10 feet apart along the plenum wall would be sufficient, each fan would need a capacity of about 8,000 cfm at 0.10 inches of static pressure. From typical manufacturers' specifications, three 30-inch

TABLE 11. Estimated capacities (in bushels) for rooms of various dimensions, with pallet bins stacked six high.

	Width in Feet (Number of Bins)								
Length (ft)	30 (8)	34 (9)	37 (10)	40 (11)	44 (12)	48 (13)	52 (14)	56 (15)	60 (16)
40	7,776	8,820	9,576	10,332	11,376	12,420	13,464	14,508	15,560
45	8,856	10,044	10,908	11,772	12,960	14,148	15,336	16,524	17,720
50	9,936	11,268	12,240	13,212	14,544	15,876	17,208	18,540	19,880
55	11,016	12,492	13,572	14,652	16,128	17,604	19,080	20,556	22,040
60	12,096	13,716	14,904	16,092	17,712	19,332	20,952	22,572	24,200
65	13,176	14,940	16,236	17,532	19,296	21,060	22,824	24,588	26,360
70	14,256	16,164	17,568	18,972	20,880	22,788	24,696	26,604	28,520
75	15,336	17,388	18,900	20,412	22,464	24,516	26,568	28,620	30,680
80	16,416	18,612	20,232	21,852	24,048	26,244	28,440	30,636	32,840
85	17,496	19,836	21,564	23,292	25,632	27,972	30,312	32,652	35,000
90	18,576	21,060	22,896	24,732	27,216	29,700	32,184	34,668	37,160
95	19,656	22,284	24,228	26,172	28,800	31,428	34,056	36,684	39,320
100	20,736	23,508	25,560	27,612	30,384	33,156	35,928	38,700	41,480

Note: for rooms with bins stacked seven or eight high, multiply the numbers in the table by 1.17 or 1.33 respectively

TABLE 12. Insulation R-values for common building materials

Material	Full Thickness R-value
fiberglass batt insulation, 3-½ inches thick	13
fiberglass batt insulation, 5-½ inches thick	19
loose fill cellulose, per inch	3.5
loose fill glass wool, per inch	3.0
vermiculite, per inch	2.2
expanded polystyrene (blue board), per inch	5.5
foil-backed polyisocyranuate, per inch	8.0
aged expanded sprayed in place polyurethane, per inch	6.3
sprayed in place urea formaldehyde, per inch	5.0
solid concrete, per inch	0.08
eight-inch concrete block	1.1
eight-inch concrete block with vermiculite fill	5.0
pine or fir lumber, per inch	1.2
metal siding	<0.01
⅜ inch plywood	0.5
½ inch plywood	0.7

diameter, one-half horsepower fans should be sufficient. Based on the fan sizes, two 30-inch motorized dampers and two 30-inch gravity shutters would also be required per room.

Controls. Proper sweetpotato curing and long-term storage requires precise control temperature, humidity, and ventilation. The level of environmental control cannot exceed the precision of the control system. The electrical controls of the heater, refrigeration system, ventilation system, and humidifier form the brain of the NHV facility. Although there are many different possible designs for this equipment, each design essentially consists of sensors and associated switching equipment. There have been two broad categories of control systems utilized in NHV facilities.

Electromechanical controls consisting of thermostats, humidistats, timers, and associated relays are wired into a central panel box. All the necessary parts and wiring can be obtained from most electrical supply dealers, and the system can be built and serviced by most licensed electricians Generally, a separate system is built to control each room. Electromechanical control systems could be designed to control several rooms, but the cost of long runs of control wiring makes this option economically unfeasible. These controls, if correctly installed, are simple and reliable. With the addition of several remote thermostats and indicator lights, the control panel may be mounted just outside the room to provide the status of the room and equipment at a glance.

Programmable Logic Controllers (PLCs), Figure 67, are industrial computers that have also been used to successfully control NHV facilities. These sophisticated devices operate the control equipment (such as heaters and humidistats) through relays in the same manner as the electromechanical controls. However, unlike the electromechanical controls, PLCs can be programmed to make various energy-saving decisions about the operation of fans, heaters, and refrigeration equipment. They also may be programmed to collect data, provide security, and sound alarms or activate automatic telephone dialing devices in emergency situations. One PLC-based system can easily control many rooms and, therefore, may be the least costly alternative for multi-room facilities. Field data suggest that PLC based systems can provide significantly more overall energy efficiency than electro-mechanical systems.

Although many parts of a PLC-based control system can be installed and serviced by a licensed electrician, the actual hardware selection and programming must be done by an experienced professional. These devices have a proven track record of reliable service in many different industries. Additionally, like many types of computer equipment, the power and versatility continue to increase as the price decreases.

Figure 67. Programmable logic controller (PLC) for an eight-room negative horizontal ventilation (NHV) facility. (PHOTO BY CCI INC.)


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TEXAS
Sweet Potatoes
SWEET MAGNOLIA
SWEET POTATOES
SAMPSON KING
NUTRITIONALLY FRESH
PURE WINNER
SWEET POTATOES
Dri-Pak
NORTH CAROLINA
SWEET POTATOES
YAMS
SHARKEY'S FINEST
sweet potatoes
Cajan
GOLD
Yams
NORTH CAROLINA
Queen Ann
WASHED AND WAXED
YAMS
SWEET POTATO
40 LBS. NET
NORTH CAROLINA
YAMS
MORNING GLORY
LOUISIANA
PORTO RICAN
SWEET POTATOES
WAYNE E. BAILEY
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Cajun
LOUISIANA
NUGGETS
SWEET POTATOES
YAMS
CAJUN GOLD
"It's Raining on Dez"
LOUISIANA BEAUREGARD YAMS
NORTH
CAROLINA
SWEET POTATOES
NATURALLY
HEALTHY
BAYOU MAID
LOUISIANA
PORTO RICAN
SWEET POTATOES
TATER GATOR
BEAUREGARD
YAMS
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YAMS
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NUTRITIONALLY
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NOYELLES
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APPENDICES

APPENDIX A. EFFECT OF PLANTING AND HARVEST DATE ON POSTHARVEST SUSCEPTIBILITY OF SWEETPOTATOES TO RHIZOPUS SOFT ROT IN NORTH CAROLINA

OBJECTIVE

The 2004 survey of thirty-two commercial sweetpotato fields suggest a correlation between planting and harvest dates and susceptibility to postharvest Rhizopus soft rot (Chapter 2). In particular, fields planted in late June and July were shown to have a higher susceptibility to *R. stolonifer*. The objective of this experiment was to further explore the relationship of planting and harvest dates to Rhizopus soft rot susceptibility under more controlled conditions.

METHODS

Plot set-up and management. Experimental plots were established in 2005 and 2006 on the Cunningham Research Station near Kinston, NC. Plots were located in a different field each year to avoid continuous rotation with sweetpotato. Herbicide, insecticide and fertilizer were applied according to standard recommendations in each year. Prior to planting, the field was disked and rows were formed. Plots were planted with cv. Beauregard vine cuttings in mid-May and mid-July (22.9 cm spacing between plants and 48.3 cm between rows). Each planting date plot consisted of 8-9.1 m long rows. One half of the plot (four rows) was harvested at 90 days after planting (DAP) and the remaining four rows were harvested at ~120 DAP (Table A.1). At harvest, roots were mechanically disked to the surface. Four replications of 20 roots (U.S. No. 1 grade) were taken from each planting/harvest date combination and hand loaded into ventilated plastic crates. The crates were transported to a storage facility at the Horticultural Crops Research Station in Clayton, NC. Roots were cured (29.4ºC at 95% relative humidity) for five days and then the temperature was dropped to 18.3ºC for the remainder of the storage period (100 days total).

Rhizopus soft rot susceptibility testing. After 100 days in storage the roots were inoculated with a Rhizopus spore suspension. The *R. stolonifer* isolate used in this study was originally collected in 1992 from a sweetpotato showing Rhizopus soft rot symptoms and signs and stored on silica crystals at 3 C (Perkins, 1962). To produce inoculum, silica crystals were transferred to potato dextrose agar (Difco, Sparks, MD) and incubated at room temperature (21-22 C) for five days. The plates were then washed with a 0.01% octylphenol ethoxylate (Triton™ X-15, Dow, New Jersey) solution and the spores removed by gently rubbing with a bent glass rod. The suspension was filtered through three layers of cheesecloth to remove mycelial fragments and adjusted to a concentration of 10^6 sporangiaspores/mL. The resulting spore suspension was stored at 3 C overnight. The day of inoculation, roots were wounded on opposite sides of the midsection with an impact wound device which created a consistent wound (8 mm diam × 1 mm deep). The wounds were immediately painted with the spore suspension using a foam brush. After inoculation roots were placed into ventilated plastic storage crates and stored at 15.6-18.3 C. At 10 days, roots were rated for incidence of Rhizopus soft rot.

Weather data. Weather data for the growing season in each year was obtained from the NC CRONOS database. An on-site weather station recorded air temperature (2 m height), soil temperature (0.1 m depth), hourly precipitation and soil moisture (0.2 m depth). Stress variables were calculated as in Chapter 2 and included high/low soil temperature stress, drought stress, and flood stress for the 1, 2, 3, and 4 weeks before harvest and the entire growing season.

Analysis of data. All statistical tests used in the data analysis were performed at the 95% confidence level. Non-transformed data was subjected to analysis of variance (PROC ANOVA, SAS Institute, Cary, NC). Least significant difference (LSD) values for planting and harvest date combination were calculated.

RESULTS AND DISCUSSION

Based on the analysis of the 2004 survey of commercial fields, we hypothesized that disease susceptibility was correlated to planting and harvest dates. However, based on this controlled study, the correlations to a specific planting or harvest date were likely confounded by environmental factors occurring prior to harvest.

Roots from plants that were planted in mid-May and harvested at 90 DAP were significantly more susceptible to Rhizopus soft rot in both years of this study when compared to the 120 DAP treatment. This indicates a possible effect of plant age on disease susceptibility, although further studies are required to determine the cause of this phenomenon (phenolic content, nutrient content, periderm thickness, etc.). It is important to keep in mind that a commercial grower would likely delay harvest longer than 90 days after planting to increase the proportion of roots which reach U.S. No. 1 grade.

However, in the mid-July planting date there was no consistent relationship in *R. stolonifer* susceptibility between the 90 DAP and 120 DAP harvest dates. In 2005, the 90 DAP harvest showed no decay while in 2006 decay incidence was over 95%. There was also a difference in the 120 DAP treatment; in 2005 decay incidence was ~25% while in 2006 the 120 DAP roots showed 80% decay. Different weather conditions between the years could be a factor; for example drought stress differed significantly between years. In the four weeks before harvest in the 90 DAP treatment, there were 5 days of drought stress in 2005 compared to 0 days of drought stress in 2006. However, no difference was detected between drought stress, or any other environmental condition, between years for the mid-July planted/120 DAP harvest treatment although disease incidence was significantly different (p=0.05).

These results strongly suggest that weather conditions prior to harvest, not specific planting or harvest dates, affect postharvest Rhizopus soft rot susceptibility. However the variability seen in this experiment indicates that further study is needed to define the relationship between weather conditions and Rhizopus soft rot susceptibility.

Table A.1. Planting and harvest dates of cv. Beauregard sweetpotatoes at the Cunningham Research Station near Kinston, NC

	Planting Date	Early Harvest Date (~90 DAP*)	Regular Harvest Date (~120 DAP)
2005			
Early planted	May 25	Aug 22	Sep 19
Late planted	July 12	Oct 14	Oct 28
2006			
Early planted	May 23	Aug 28	Sep 25
Late planted	Jul 13	Oct 12	Oct 25

*Days after planting

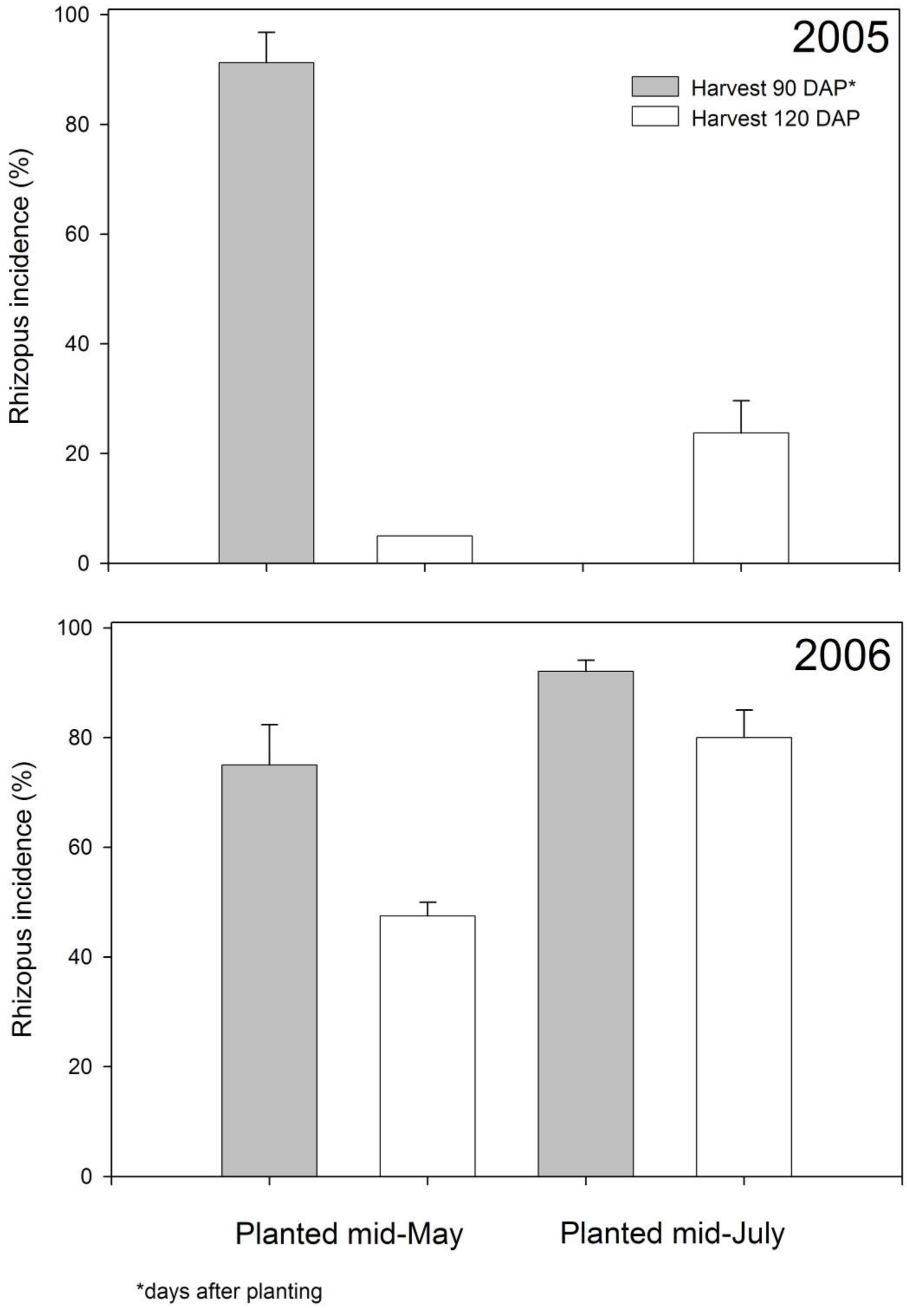

Figure A.1. The relationship between planting and harvest dates to susceptibility of sweetpotatoes to postharvest Rhizopus soft rot (Kinston, NC; 2005 and 2006).

APPENDIX B. EFFECT OF PREHARVEST APPLICATIONS OF THE HERBICIDE FLUMIOXAZIN ON POSTHARVEST SUSCEPTBILITY OF SWEETPOTATOES TO RHIZOPUS SOFT ROT

OBJECTIVE

Certain herbicide active ingredients are suspected of altering sweetpotato foliage and root physiology. In the first two years (2004 and 2005) of the preharvest effects on disease susceptibility study (Chapter 2), statistically significant correlations were seen between Rhizopus soft rot susceptibility and applications of herbicides containing the active ingredients flumioxazin (Valor®) and clomazone (Command®). This experiment was undertaken to determine the effect of variable rates of preharvest applications of flumioxazin [combined with several rates of s-metolachlor (Dual®)] on Rhizopus soft rot susceptibility under replicated conditions.

METHODS

This study was conducted in 2007 at the Cunningham Research Station near Kinston, NC in cooperation with K. Jennings (Horticultural Science, NCSU). Three rates of pre-transplant applied flumioxazin (0, 2.5, and 3.0 oz/acre) combined with three rates of pre-transplant applied s-metolachlor (0.75, 1.0, 1.25 oz/acre) were compared to a weed-free check. Beauregard vine cuttings were transplanted on 6 Jun 07, 3 days post-application, with a 30.5 cm plant spacing and a 48.3 cm row spacing. Experimental design was a randomized block design with four 7.6 m long replications per application rate treatment. The weed-free check was maintained by hand and mechanical weeding at weekly intervals. The primary weed species present was *Amaranthus* spp. (commonly known as pigweed).

At harvest (9 Sep 07), twenty roots were sampled from each replication and placed into ventilated plastic crates. The crates were transported to a storage facility in Clayton, NC. Roots were cured (29.4ºC at 95% relative humidity) for five days and then the temperature was dropped to 18.3ºC for the remainder of the storage period. After 100 days in storage the roots were inoculated with a Rhizopus spore suspension. The *R. stolonifer* isolate used in this study was originally collected in 1992 from a sweetpotato showing Rhizopus soft rot symptoms and signs and stored on silica crystals at 3 C (Perkins, 1962). To produce inoculum, silica crystals were transferred to potato dextrose agar (Difco, Sparks, MD) and incubated at room temperature (21-22 C) for five days. The plates were then washed with a 0.01% octylphenol ethoxylate (Triton™ X-15, Dow, New Jersey) solution and the spores removed by gently rubbing with a bent glass rod. The suspension was filtered through three layers of cheesecloth to remove mycelial fragments and adjusted to a concentration of 10^6 sporangiospores/mL. The resulting spore suspension was stored at 3 C overnight. The day of inoculation, roots were wounded on opposite sides of the midsection with an impact wound device which created a consistent wound (8 mm diam × 1 mm deep). The wounds were immediately painted with the spore suspension using a foam brush. After inoculation, roots were placed into ventilated plastic storage crates and stored at 15.6-18.3 C. At 10 days, roots were rated for incidence of Rhizopus soft rot.

RESULTS AND DISCUSSION

In this study, no relationship was observed between flumioxazin application combined with s-metolachlor and Rhizopus soft rot susceptibility, as disease susceptibility was very low in all treatments (Table A.2). Flumioxazin applications are known to damage aboveground foliage of Beauregard sweetpotatoes, while clomazone applications result in little to no damage (Kelly et al., 2006). The effect of clomazone applications on Rhizopus soft rot susceptibility of sweetpotatoes has not yet been confirmed in controlled studies. Additional studies under conditions of greater Rhizopus soft rot incidence are necessary to determine the effect of flumioxazin on postharvest susceptibility of sweetpotatoes to Rhizopus soft rot.

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Table A.2. Effect of flumioxazin application on postharvest susceptibility to Rhizopus soft rot.

Flumioxazin + s-metolachlor (oz/acre)	Rhizopus incidence (%)	
0 + 0 (Weed-free check)	0	a*
0 + 0.75	0	a
0 + 1.0	0	a
0 + 1.25	0	a
2.5 + 0.75	0	a
2.5 + 1.0	0	a
2.5 + 1.25	0	a
3.0 + 0.75	0	a
3.0 + 1.0	0.05	a
3.0 + 1.25	0	a

*numbers followed by the same letter are not significantly different (*P*=0.05)

APPENDIX C. EFFECT OF CROP ROTATION ON POSTHARVEST SUSCEPTIBILITY OF SWEETPOTATOES TO RHIZOPUS SOFT ROT IN NORTH CAROLINA

OBJECTIVE

The results of a survey of thirty-two commercial fields in 2004 indicated a significant correlation between the previous year's rotation crop and increased susceptibility of sweetpotatoes to postharvest Rhizopus soft rot (Chapter 2). The objective of this experiment was to determine the effect of different rotation crops on postharvest susceptibility of sweetpotatoes to Rhizopus soft rot under replicated conditions.

METHODS

Experimental plots of rotation crops were established at the Cunningham Research Station near Kinston, NC (Table A.3). The experimental design was a randomized complete block with six rotation crop treatments (sweetpotato, tobacco, corn, fallow, cotton and soybean) and four replications per rotation treatment. The experiment was conducted twice and staggered in time (2004 and 2005). Herbicide, insecticide and fertilizer were applied according to general recommendations for each crop. Prior to planting sweetpotatoes as the final rotation, the entire field was disked, fumigated and rows were formed. Sweetpotato cv Beauregard vine cuttings were transplanted with 30.5 cm between plants and a 48.3 cm spacing between rows. Weather data for the growing season in each year was obtained from the NC CRONOS database. An on-site weather station recorded air temperature (2 m height), soil temperature (0.1 m depth), hourly precipitation and soil moisture (0.2 m depth).

At harvest, twenty roots were sampled from each rotation treatment replication and placed into ventilated plastic crates. The crates were transported to a storage facility at the Horticultural Crops Research Station in Clayton, NC. Roots were cured (29.4ºC at 95% relative humidity) for five days and then the temperature was dropped to 18.3ºC for the remainder of the storage period. After 100 days in storage the roots were inoculated with a Rhizopus spore suspension. The *R. stolonifer* isolate used in this study was originally collected in 1992 from a sweetpotato showing Rhizopus soft rot symptoms and signs and stored on silica crystals at 3 C (Perkins, 1962). To produce inoculum, silica crystals were transferred to potato dextrose agar (Difco, Sparks, MD) and incubated at room temperature (21-22 C) for five days. The plates were then washed with a 0.01% octylphenol ethoxylate (Triton™ X-15, Dow, New Jersey) solution and the spores removed by gently rubbing with a bent glass rod. The suspension was filtered through three layers of cheesecloth to remove mycelial fragments and adjusted to a concentration of 10^6 sporangiospores/mL. The resulting spore suspension was stored at 3 C overnight. The day of inoculation, roots were wounded on opposite sides of the midsection with an impact wound device which created a consistent wound (8 mm diam × 1 mm deep). The wounds were immediately painted with the spore suspension using a foam brush. After inoculation, roots were placed into ventilated plastic storage crates and stored at 15.6-18.3 C. At 10 days, roots were rated for incidence of Rhizopus soft rot.

RESULTS AND DISCUSSION

There were significant differences in Rhizopus soft rot susceptibility between the two years of the study (Figure A.2). Across all rotation crop treatments, the mean decay was 9.1% in 2005 and 72.6% in 2006. Within each of the two years, however, there was no significant difference in disease susceptibility among the different rotation crops. These results suggest that the relationship between crop rotation and disease susceptibility seen in the survey fields (Chapter 2) is most likely incidental.

An analysis of the weather conditions at the Cunningham Research Station show differences between 2005 and 2006. The average soil temperature and soil moisture for the 2005 growing season was 27.3 C and 0.19 m^3/m^3, respectively. During the 2006 growing season, however, the average soil temperature was colder (26.3 C) and the average soil moisture was higher (0.26 m^3/m^3) than in 2005. Therefore, it is more likely that differences in weather conditions between years is a main factor affecting root physiology which in turn effects on Rhizopus soft rot susceptibility.

Table A.3. Crop rotation scheme tested at the Cunningham Research Station near Kinston, NC, 2003-2006.

	Year 1 2003	winter cover	Year 2 2004	winter cover	Year 3 2005	winter cover	year 4 2006
Block 1							
	soybean	wheat	sweetpotato	wheat	sweetpotato		
	soybean	wheat	tobacco	wheat	sweetpotato		
	soybean	wheat	corn	wheat	sweetpotato		
	soybean	wheat	fallow	wheat	sweetpotato		
	soybean	wheat	cotton	wheat	sweetpotato		
	soybean	wheat	soybean	wheat	sweetpotato		
Block 2							
	soybean	wheat	sweetpotato	wheat	sweetpotato	wheat	sweetpotato
	soybean	wheat	sweetpotato	wheat	tobacco	wheat	sweetpotato
	soybean	wheat	sweetpotato	wheat	corn	wheat	sweetpotato
	soybean	wheat	sweetpotato	wheat	fallow	wheat	sweetpotato
	soybean	wheat	sweetpotato	wheat	cotton	wheat	sweetpotato
	soybean	wheat	sweetpotato	wheat	soybean	wheat	sweetpotato

Shaded cells indicated sweetpotato plots that were harvested and tested for Rhizopus soft rot susceptibility

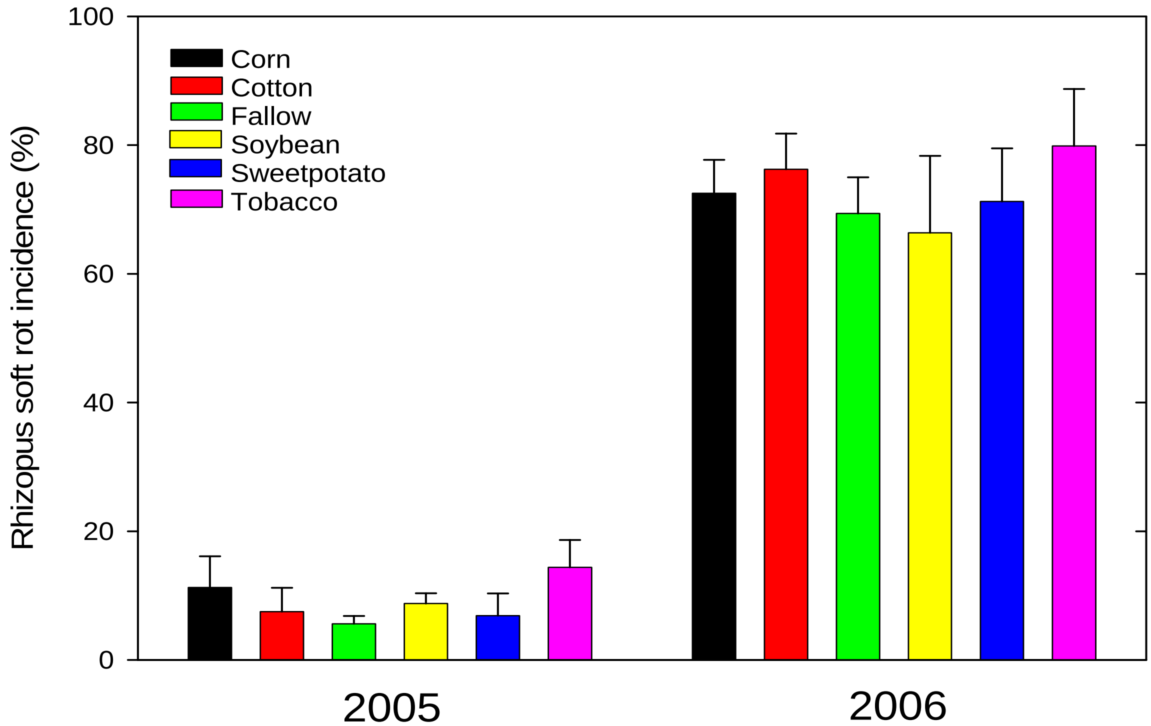

Figure A.2. The relationship between previous crop and susceptibility of sweetpotatoes to postharvest Rhizopus soft rot (Kinston, NC).